AN INVESTIGATION OF THE EFFECTS OF VARIATIONS IN COARSE AGGREGATE GRADATION ON PROPERTIES OF PORTLAND CEMENT CONCRETE

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BY

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JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND

INDIANA STATE HIGHWAY COMMISSION

Final Report

AN INVESTIGATION OF THE EFFECTS OF VARIATIONS IN COARSE AGGREGATE GRADATION ON PROPERTIES OF PORTLAND CEMENT CONCRETE

TO:	J. F. McLaughlin, Director Joint Highway Research Project	May 3, 1973
		File: 5-9-10
FROM:	H. L. Michael, Associate Director Joint Highway Research Project	Project: C-36-42J

The attached Final Report titled "An Investigation of the Effects of Variations in Coarse Aggregate Gradation on Properties of Portland Cement Concrete" has been authored by Mr. Stephen D. Baker, Graduate Assistant in Research on our staff. Professor C. F. Scholer directed the research. Mr. Baker also used the report as his thesis for the MSCE degree.

The study was concerned with determination of the extent to which typical variations in coarse aggregate gradation affect the properties of a highway concrete paving mixture. The findings include significant affects on value and uniformity of slump and strength and inconsequential impact on density of the concrete if reasonable compaction effort is applied.

Application of the Results is included as a section of the report where suggestions are made relative to specifications, a revised system of gradation control and payment adjustment for non-conformance with statistical specifications.

The Report is presented to the Board for acceptance as fulfillment of the objectives of the Study.

Respectfully submitted,

Harold L. Michael

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Associate Director

HLM:ms

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by

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Joint Highway Research Project

File: 5-9-10

Project: C-36-42J

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Engineering Experiment Station
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ACKNOWLEDGMENTS

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Sincere appreciation is expressed to Doctor C. F. Scholer for his assistance during all phases of the investigation and preparation of this thesis and to Doctors J. A. Havers and V. L. Anderson for their advice and review of the thesis.

The writer also wishes to thank his wife, Paula, for her patience and support.

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ABSTRACT

Baker, Stephen Daugherty. M.S.C.E., Purdue University, May 1973. An Investigation of the Effects of Variations in Coarse Aggregate Gradation on Properties of Portland Cement Concrete. Major Professor: Charles F. Scholer.

This investigation was concerned with determining the extent to which typical variations in coarse aggregate gradation affect the properties of a highway concrete paving mixture.

The sole variable under investigation was coarse aggregate grading. Numerous batches of concrete, each containing like materials and proportions except for the varying gradation, were mixed and tested in the laboratory. The various gradings taken as a set represent the fluctuations in gradation of natural gravel estimated to occur in typical highway construction. The estimates were obtained from statistical studies of gradation variability by state highway agencies and by the author's statistical analyses of Indiana State Highway Commission sieve analysis reports.

Each batch was tested for compressive strength, slump and unit weight after compacting with three levels of effort. The results of these tests were analyzed in a manner which allowed evaluation of the contribution of coarse aggregate gradation variability to overall property variation during typical paving operations.

Slump and strength were found to be significantly affected by variations in gradation of gravel. Also, gradation was shown to affect uniformity of compressive strength of paving concrete as much as uniformity of slump.

In regards to compactability, the effect of variation in gradation on density was shown to be inconsequential if a reasonable compaction effort was applied.

INTRODUCTION

The variability of portland cement concrete properties is caused by variations in the materials and the production process. Major sources of variation include: gradation, moisture content, shape and texture of both fine and coarse aggregate; composition, age and condition of the cement and admixtures; and temperature, batching and mixing of the materials. A more complete listing has been presented by Mercer [1].* Concrete production specifications set limits on the variation allowed in some of these sources. Coarse aggregate gradation, in particular, has traditionally been evaluated by comparing results of sieve analyses with a specified gradation envelope. The boundaries or limits of typical envelopes have been established on the basis of subjective conclusions concerning: (a) the level of variation attainable by practical processing techniques and (b) the effect of variation on the concrete. The research reported herein has been an investigation of the latter consideration. It has been directed toward evaluating the quantitative effect of variation in coarse aggregate gradation on the workability and strength of a highway concrete mix.

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* Numbers in brackets refer to references in the Bibliography.

The variation in coarse aggregate gradation within a given production situation is nothing more than the occurrence of differences in grading, within and between batches of concrete, caused by segregation, degradation or inherent randomness. Though little work has been directed toward the effect of variation specifically, extensive research has been done on the influence of coarse aggregate gradings on the properties of concrete. These studies provide information from which the qualitative effects of variability can be inferred.

In 1907, Fuller and Thompson [2] concluded that a smooth grading curve provided the most dense aggregate condition and the highest strength of concrete. Contrary to this, Talbot and Richart [3] obtained harsh unworkable concrete from aggregate graded to produce maximum density and found no direct relationship between strength and gradation. The prevailing attitude during the 1920's, with regard to the influence of aggregate grading on concrete, was summarized by McMillan [4]. He stated that "... change in strength is not due as is so apt to be thought, to the change in grading as such, but results from the difference in water required to maintain the given consistency." Thus, for a period of years research regarding gradation was directed toward its effect on consistency or workability. Investigators developed various methods of measuring workability, though none can be considered an absolute measure

due to the relative nature of workability in regards to the use of the concrete and due to the several characteristics comprising workability.

Powers [5] measured slump and remolding effort resulting from different combinations of coarse aggregate in concrete mixes which had varied proportions of sand and cement paste. The cement required to maintain a given consistency was found to be unaffected by a wide variety of coarse aggregate gradings if proper adjustments were made in the amount of sand. However, Powers explicitly emphasized this should not be construed to mean variation in coarse aggregate gradation was not important, because in practice compensating adjustments in sand cannot be made.

An investigation by Glanville [6] again showed strength to be unaffected by even "... quite large changes in grading..." if the proportions of sand and gravel were varied satisfactorily. During the investigation he developed the compacting factor test and used it to establish satisfactory proportions of mix components associated with three levels of workability in combination with four gradings of coarse aggregate.

In 1960 Walker and Bloem [7] dispelled traditional beliefs about strength being unaffected by coarse aggregate gradation. They showed strength to be higher for continuous gradings with relatively smaller maximum aggregate size even when the cement factor and slump were the same.

Gap gradings have been found to require less cement content for the same workability. Li, in a study comparing the workability of mixes with 1 1/2 inch and less maximum aggregate size, obtained more workable concrete from gap gradings than from continuous gradings, other factors (water-cement ratio, cement content, maximum size of aggregate) being the same [8]. He used both slump and Vebe time [9] to evaluate workability.

The following pertinent deductions can be made from these previous investigations by considering variation as the occurrence of fine, coarse or gap gradings:

1. Variation in coarse aggregate gradation causes changes in the workability of concrete; relatively lower workability resulting from finer gradings [5, 6].
2. Variation causes changes in the compressive strength of concrete; gradings with smaller maximum size resulting in higher strength [7].
3. Variations in the form of gap gradings may not cause changes in workability if the mix proportions are suitable [8].
4. The cement mortar-coarse aggregate volume ratio affects the sensitivity of the mix to changes in grading [6].

An experiment which parallels the investigation reported herein was done by Tynes of the U. S. Army Corps of Engineers

[10]. Three gradings - the finest, coarsest and middle gradings specified for mass concrete by the Corps of Engineers Standard Guide Specification for Concrete - were entered in mass concrete mixtures which were tested for consolidation time, slope workability, modulus of elasticity and compressive strength. The results showed no significant differences statistically but indicated a trend of decreased workability from the coarse to fine aggregate gradings. Tynes concluded that mass concrete containing crushed limestone or natural gravel meeting the gradation specification did not show significant differences in compressive strength or workability.

The conclusions made by Tynes were applicable to concrete produced with gradings not exceeding the specification boundaries. The presumption that the extent of gradation variability in highway construction is within typical specification limits has been shown to be invalid by statistical evaluations of concrete aggregates. In a study of a representative South Carolina highway project made by Fletcher and Mills, twenty percent of the individual sieve analysis results failed to conform to the specifications limits [11]. The details of their statistical analyses are discussed more completely in the section: Selection of Gradings Investigated.

The variability in properties typically used for control of highway concrete has been measured. A summarization of

several studies has been made by Newlon [12]. He cited the results of field investigations done by state highway organizations in conjunction with the Bureau of Public Roads which show representative magnitudes of variation (standard deviation) in slump, strength and unit weight for pavement concrete. The variations measured in the studies resulted from all the sources associated with typical highway concrete production, among them variation in coarse aggregate gradation such as reported by Fletcher and Mills. A more detailed discussion of the results of field studies is presented in the section: Presentation and Discussion of Results.

PURPOSE AND SCOPE

The purpose of this research was to: (a) investigate the effect of variation in coarse aggregate gradation on portland cement concrete, (b) determine the quantitative effect of variation in coarse aggregate (natural gravel) gradation on selected properties of a concrete mix designed in accordance with the Indiana State Highway Commission's (ISHC) requirements for slipform pavement, (c) determine the importance of coarse aggregate gradation variability as a factor in the variation of strength, slump and unit weight of highway paving concrete and (d) develop a general procedure which can be used to evaluate the importance of variation in coarse aggregate gradation.

The magnitude of gradation variability investigated was that associated with typical highway concrete production. An estimate of this variability (standard deviation) was obtained from the statistical studies of other investigators and from the author's statistical analyses of sieve analysis data from ISHC Aggregate Inspectors Test Reports. Batches of concrete which contained gradings having percent passing curves within an envelope bounding the estimated gradation variability were mixed in the laboratory and tested for slump,

unit weight, compacting factor [6], remolding effort [5] and compressive strength.

The investigation was limited to a single set of mix proportions and to natural gravel from one plant and one pit. Other factors affecting the variability of the concrete were reduced to a practical minimum. Cement from within a continuous run of the source plant and sand from a single stockpile were used throughout the investigation. The aggregates, both fine and coarse, were dried to eliminate the effect of varying moisture content. Though all variation from the many sources could not be totally eliminated, every effort was made to establish gradation as the sole variable during the testing.

PLAN OF INVESTIGATION

The sole variable during the investigation, insofar as possible, was the coarse aggregate gradation within a concrete mixture designed to meet the ISHC requirements for slipform pavement. The particular gradings examined were representative of all gradings within a percent passing envelope covering the variation estimated to occur in typical highway concrete gravel.

Natural gravel from a single stockpile used as a source of concrete aggregates by the ISHC was separated into the sizes included in the ISHC No. 5 [13] coarse aggregate sieve series. Batches of concrete containing known gradings of recombined gravel were mixed in the laboratory and tested for compressive strength and workability. The variations of all other material quantities and characteristics were minimized to the extent practically possible.

The laboratory tests performed on each batch were intended to provide data which could be used to: (a) evaluate the effect of gradation on properties used to control and measure the quality and uniformity of field produced concrete, (b) detect changes in workability and (c) evaluate the interrelationship of coarse aggregate grading, strength, unit weight and compaction effort for a single set of mix

proportions. Standard slump, compressive strength and unit weight tests were made in order to evaluate the effect of grading on the commonly measured properties of field produced concrete. A compacting factor apparatus and remolding apparatus were used to observe effects of grading on workability which might not be detected by the slump test. Unit weight or density measurements were also made after vibrating the concrete for ten and twenty seconds. This unit weight data combined with that from the standard rodded and compacting factor unit weight tests allowed evaluation of the effect of grading on compactability. Those specimens observed to bleed excessively during vibration were sawed after hardening and visually examined for segregation. Other specimens were examined microscopically to verify air content.

SELECTION OF GRADINGS INVESTIGATED

Statistical evaluations carried out by state highway organizations have identified the magnitude of variation (standard deviation) in coarse aggregate gradation occurring in paving projects under their jurisdiction. The results of two such studies are shown in Table 1 along with the results of analyses of gradation within stockpiles at four aggregate plants used by the Indiana State Highway Commission (ISHC). The latter results were obtained from statistical analyses of data (percent passing for each sieve) recorded on ISHC Aggregate Inspectors Test Reports. The material in all four stockpiles was natural gravel used by the ISHC for No. 5 concrete aggregate. The test reports did not include results of tests which did not meet the No. 5 grading requirements, as is accepted practice. The deletion of these "failures" from the statistical analyses resulted in smaller estimates of standard deviation than actually occur. However, the estimates showed the variation in ISHC aggregate gradation to be similar to that reported in the referenced studies. Based on the standard deviations listed in Table 1, an estimate of the variation in percent passing each sieve ($\hat{\sigma}_s$) was established for use in this investigation. These estimates are listed in Table 2 and were considered

TABLE 1

STANDARD DEVIATION OF PERCENT (BY WEIGHT) PASSING

Source of Data	Sieve Size					
	1"	3/4"	1/2"	3/8"	No. 4	No. 8
[14] Louisiana Department of Highways: Stockpiles*	3.15	6.38	5.17	—	0.85	—
[11] S. Carolina State Highway Department: Concrete**	1.36	—	9.0	—	1.89	0.90
Source**	1.42	—	4.54	—	0.96	0.29
Belt**	1.52	—	10.94	—	3.35	0.96
ISHC Aggregate Inspectors Test Reports (30 for each stockpile):						
Stockpile 1**	1.78	5.28	5.98	3.92	0.75	0.39
Stockpile 2**	2.78	4.40	7.30	7.38	2.17	0.65
Stockpile 3**	2.44	5.56	5.72	3.47	0.52	0.32
Stockpile 4**	2.23	5.05	8.19	5.85	0.63	0.26

* Material variation

** Testing, sampling and material variation

TABLE 2

ESTIMATES OF STANDARD DEVIATION USED FOR
ESTABLISHING TYPICAL GRADATION VARIABILITY

Sieve Size					
1"	3/4"	1/2"	3/8"	No. 4	No. 8
3.0	8.0	9.0	8.0	2.0	1.0

overestimates since they exceeded the combined material and testing standard deviations of the reported analyses but were applied as material variation in the investigation.

The analyses of data from the ISHC test reports also showed the average percent passing for each sieve to closely approximate the norm of the No. 5 gradation limits specified by the ISHC Standard Specification [13]. The term "norm" is used to identify the grading which is the average of the percent passing limits for each sieve. Table 3 lists the average percent passing for each of the four stockpiles, the No. 5 limits and the norm. The estimates listed in Table 2 were applied to the norm to obtain the $3\hat{\sigma}$ limits in Figure 1, which shows the relationship of production variation and the No. 5 gradation limits. The envelope outside the $3\hat{\sigma}$ limits in Figure 1 was established as the boundary for the range in grading to be investigated. Figures 2 - 8 show the gradings

TABLE 3

COMPARISON OF CUMULATIVE PERCENT PASSING

Sieve Size	ISHC No. 5 Limits	Norm Grading	Average for Stockpile			
			1	2	3	4
1 1/2"	100	100.0	100.0	100.0	100.0	100.0
1"	98 - 85	91.5	90.2	91.4	93.0	91.9
3/4"	85 - 60	72.5	70.5	70.0	74.4	71.0
1/2"	60 - 30	45.0	45.3	39.8	43.7	43.0
3/8"	35 - 10	22.5	25.1	17.9	23.0	23.9
No. 4	10 - 0	5.0	1.8	0.8	4.2	3.0
No. 8	5 - 0	2.5	1.0	0.6	1.4	1.5
No. 200	1 - 0	0.5	—	—	—	—

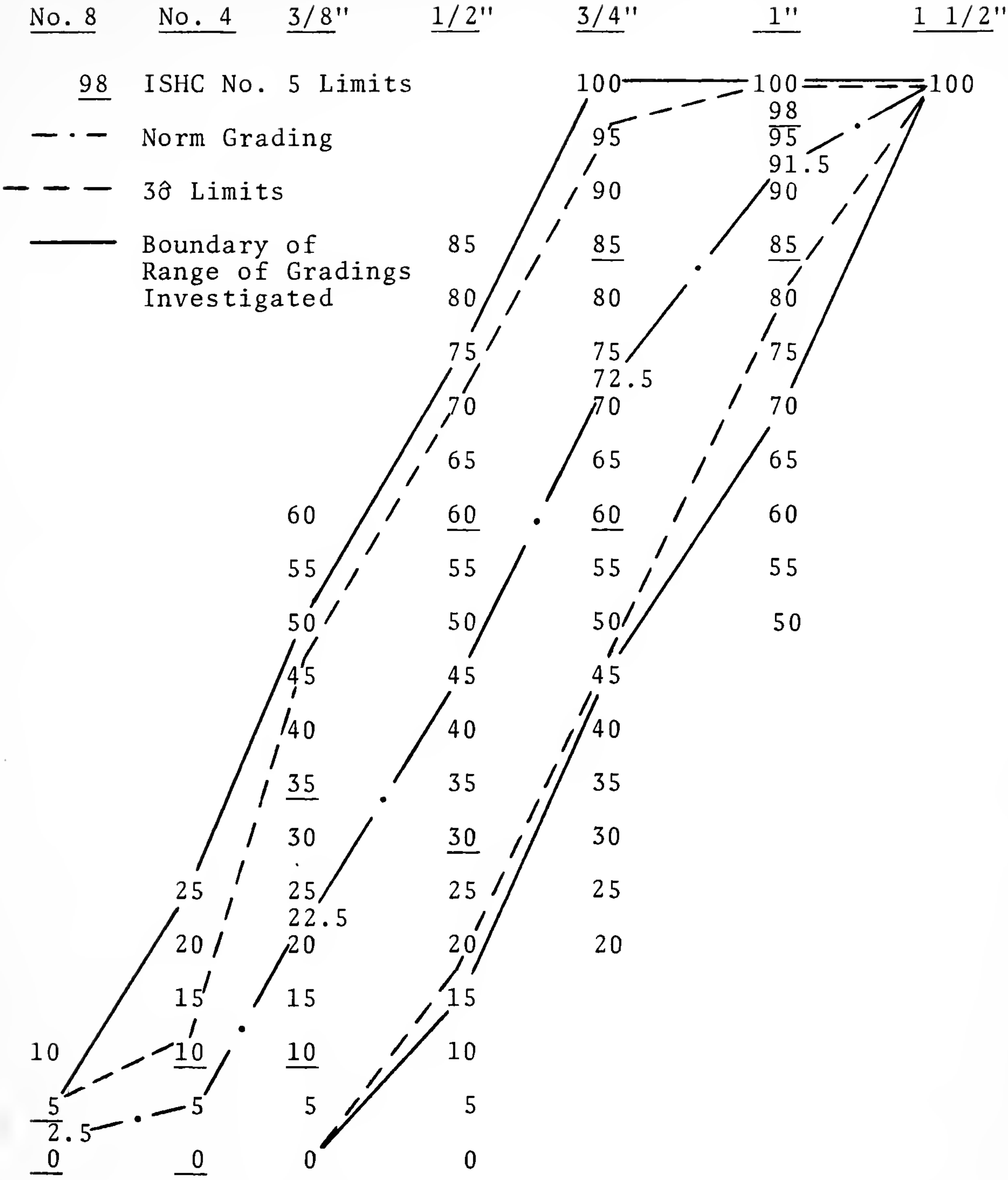

FIGURE 1. RANGE OF GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

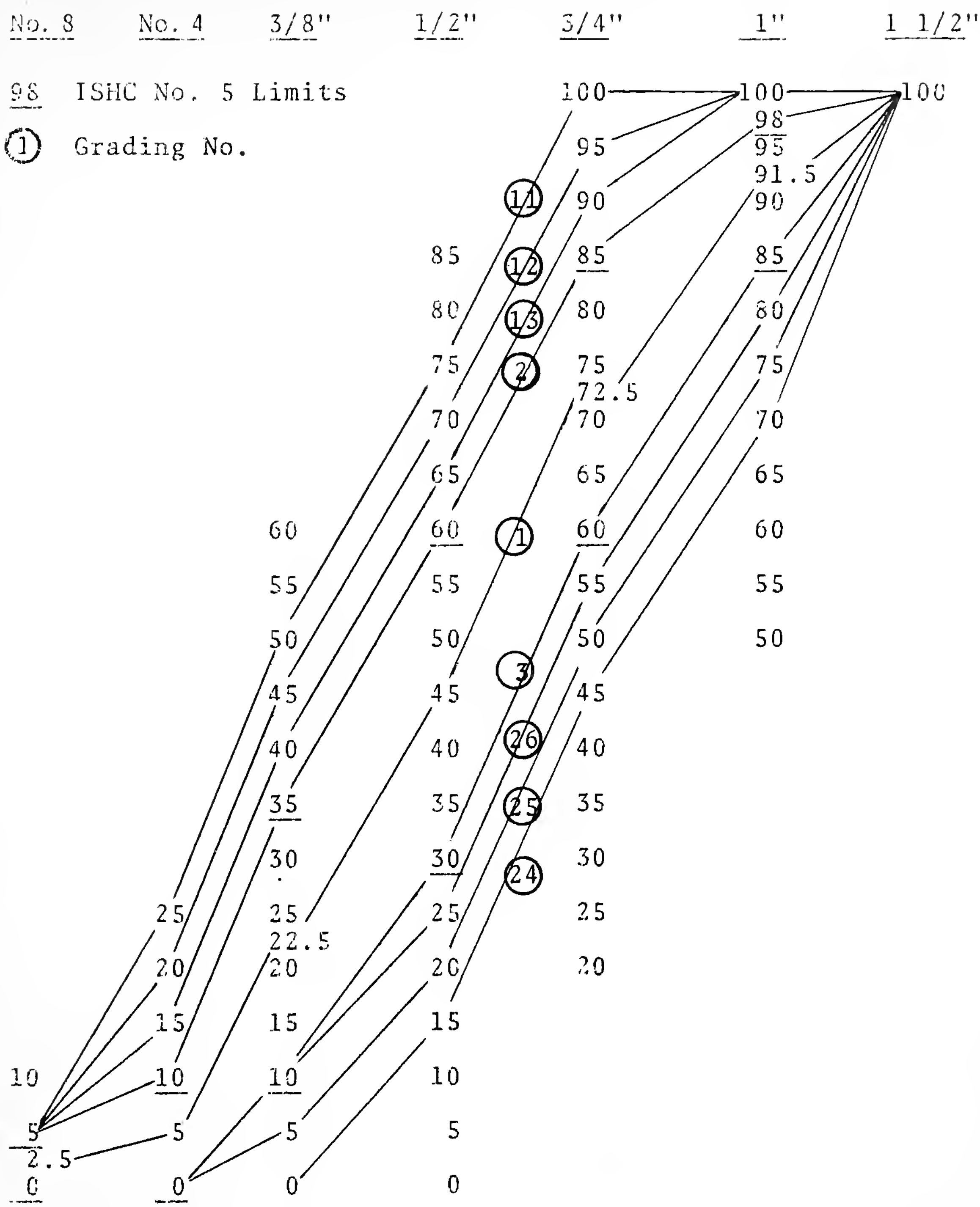

FIGURE 2. GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

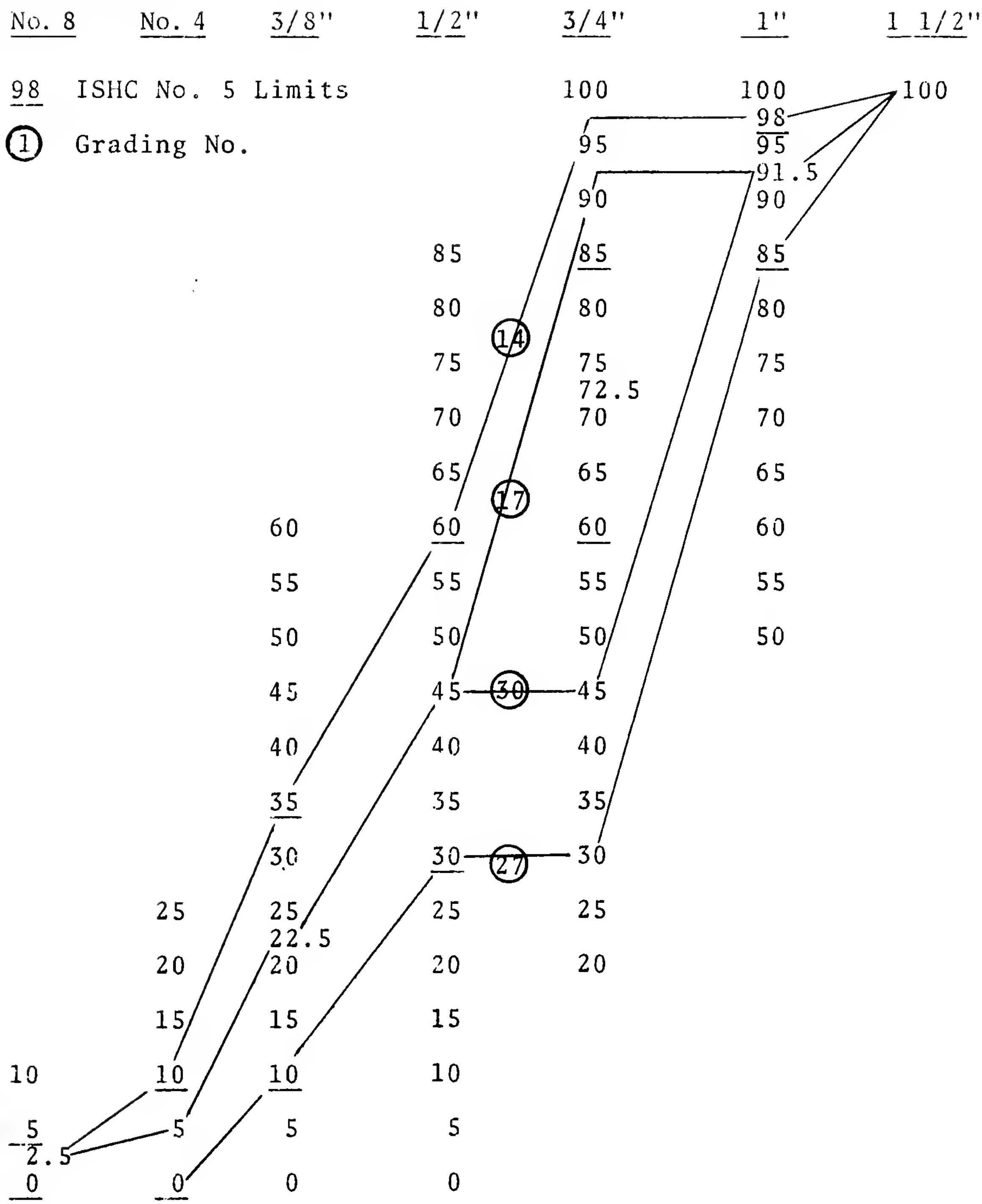

FIGURE 3. GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

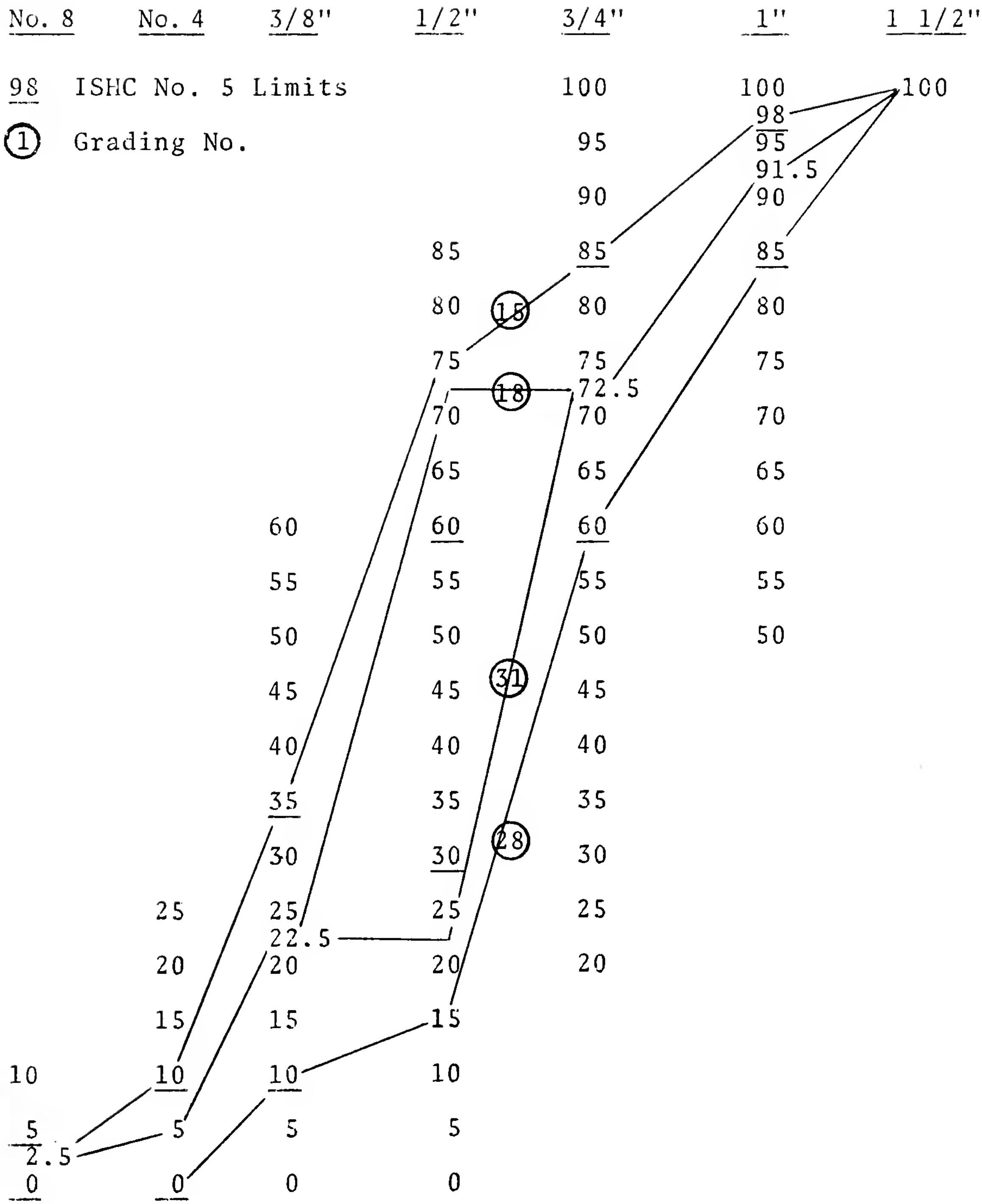

FIGURE 4. GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

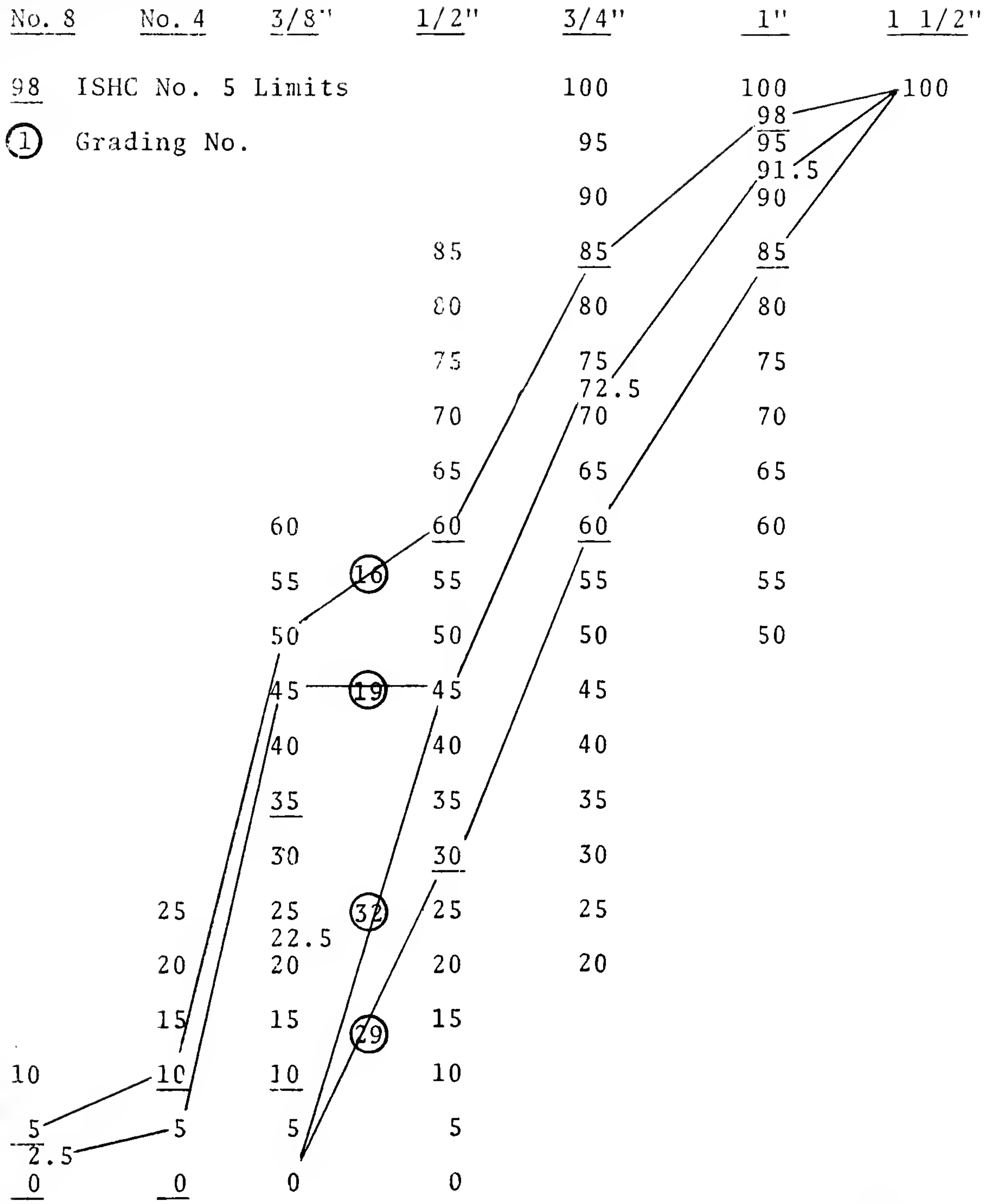

FIGURE 5. GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

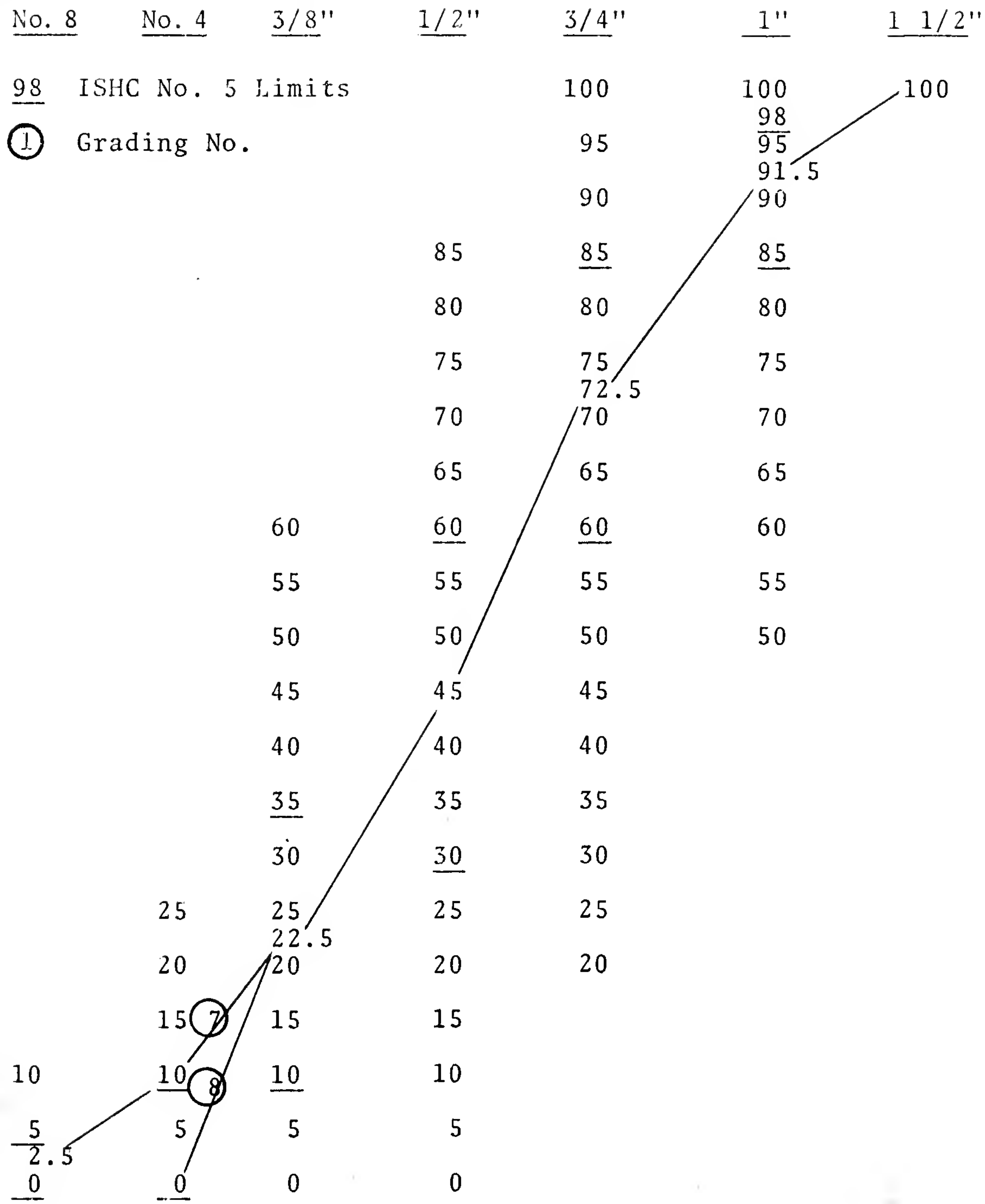

FIGURE 6. GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

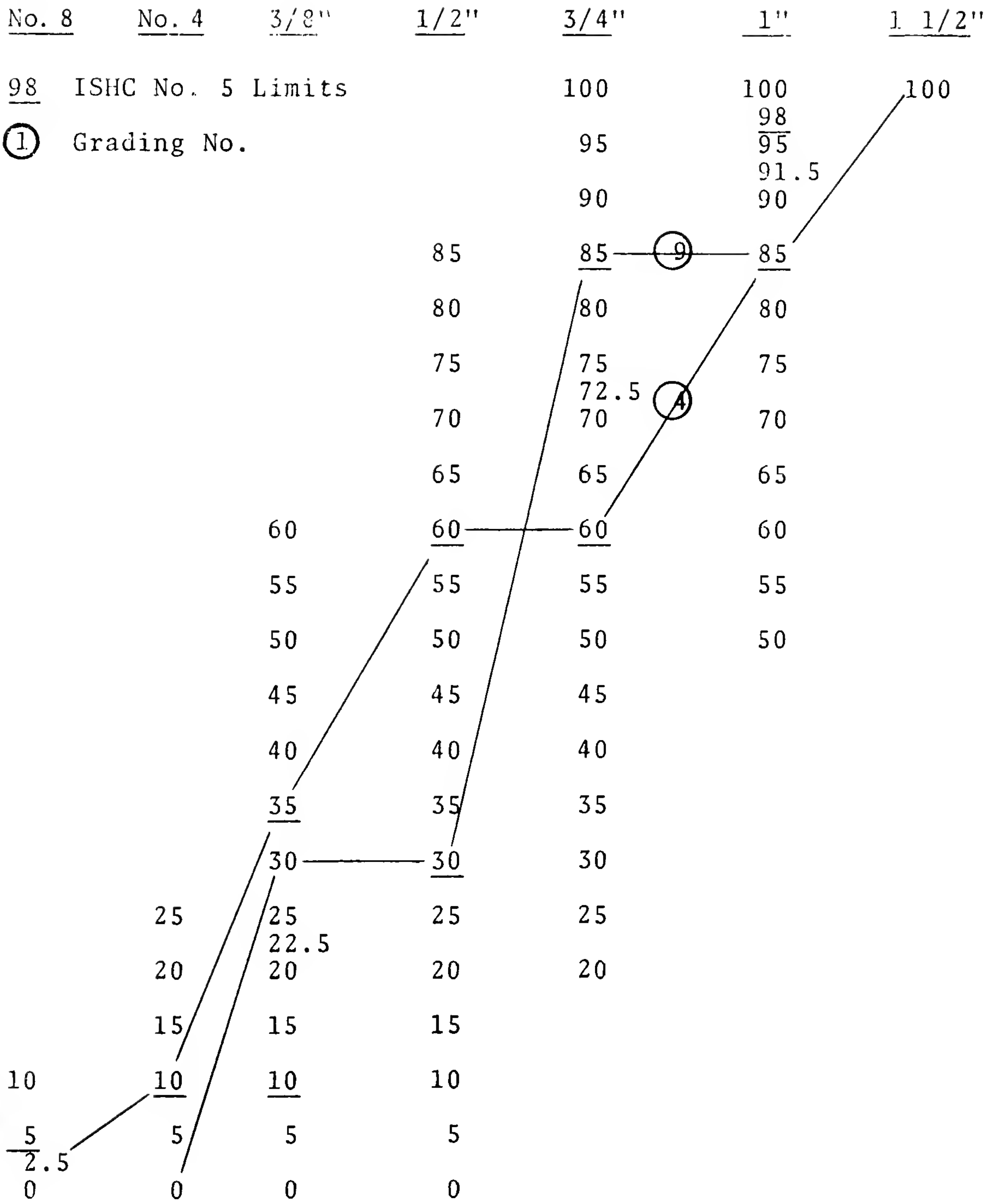

FIGURE 7. GRADINGS INVESTIGATED - CUMULATIVE

PERCENT PASSING VS. SIEVE SIZE

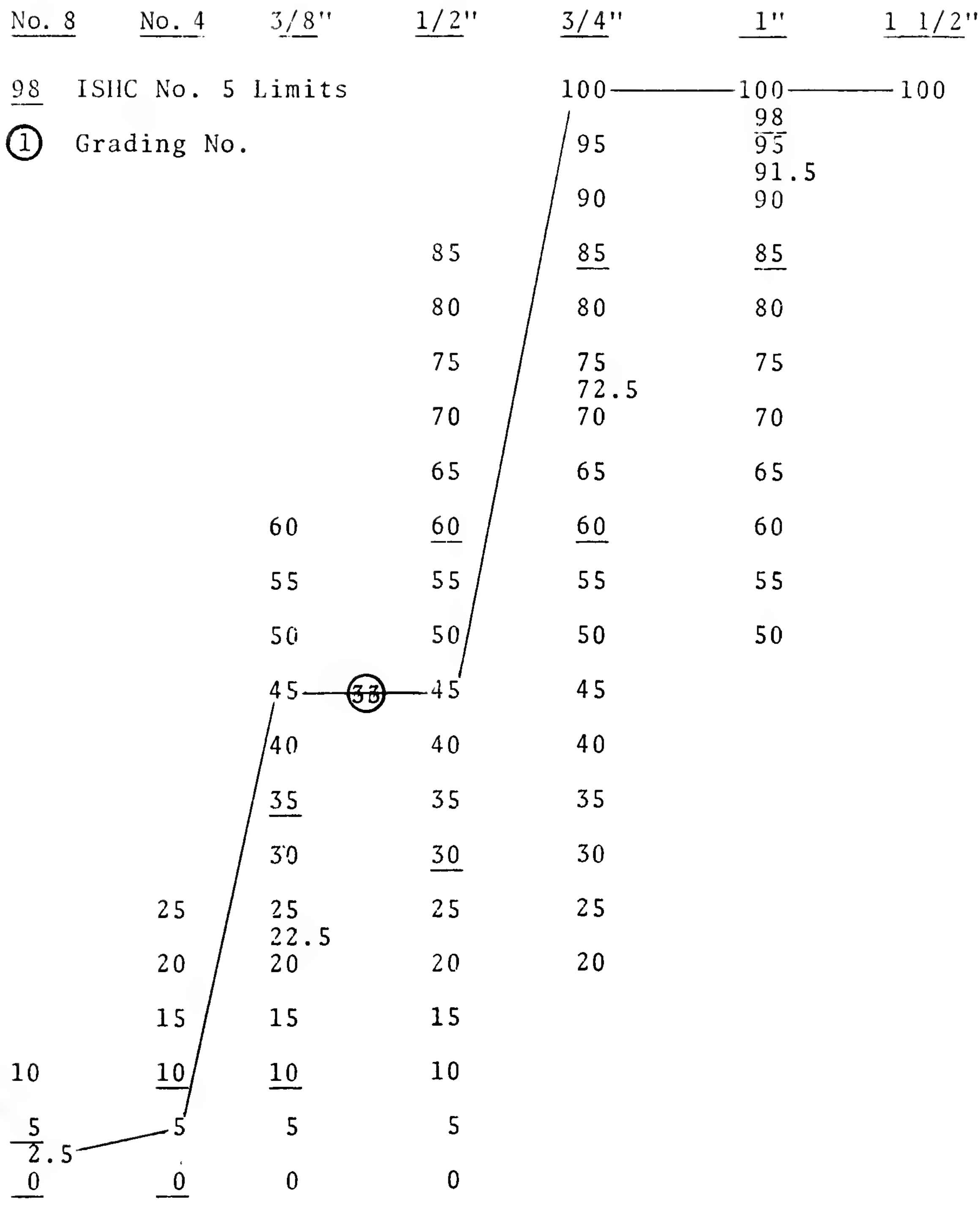

FIGURE 8. GRADINGS INVESTIGATED - CUMULATIVE PERCENT PASSING VS. SIEVE SIZE

of major interest which were examined, and Table 4 lists percents passing for all gradings examined. The gradings were representative of all possible 3σ variations and included (a) fine, coarse and intermediate continuous gradings, (b) fine and coarse gradings "gapped" on each sieve and (c) an intermediate gap grading. The gradings were also selected with the intent of evaluating the relative effect of like variation (i.e. equal in level) of the various sizes. The inclusion of continuous gradings having $\pm\ 3\hat{\sigma}$ variation occurring simultaneously on each sieve is possibly more of an overestimation than that mentioned above. Statistically, the assumption of a normal distribution in regards to the concurrent variation on each sieve is conservative, for a binomial distribution might better describe the combinations of individual variation which occur. More practically interpreted, a positive variation on one sieve might more typically be accompanied by negative variation on one or more of the other sieves than by other positive variations. In defense of the possible overestimation, it should be pointed out that a lens of fine or coarse particles in a stockpile could result in the extreme gradings represented by $\pm\ 3\hat{\sigma}$ continuous gradings.

It is noted the ISHC No. 5 coarse aggregate gradation envelope is located at approximately the $1.5\hat{\sigma}$ level of the estimated gradation variation. This indicates that approximately fifteen percent of the sieve analysis test results

TABLE 4

CUMULATIVE PERCENT PASSING FOR EACH GRADING INVESTIGATED

Grading	Sieve Size						
No.	1 1/2"	1"	3/4"	1/2"	3/8"	No. 4	No. 8
1	100.0	91.5	72.5	45.0	22.5	5.0	2.5
2	100.0	98.0	85.0	60.0	35.0	10.0	2.5
3	100.0	85.0	60.0	30.0	10.0	0.0	0.0
4	100.0	85.0	60.0	60.0	35.0	10.0	2.5
5	100.0	98.0	70.0	30.0	30.0	0.0	0.0
6	100.0	91.5	70.0	30.0	10.0	0.0	0.0
7	100.0	91.5	72.5	45.0	22.5	10.0	2.5
8	100.0	91.5	72.5	45.0	22.5	0.0	0.0
9	100.0	85.0	85.0	30.0	30.0	0.0	0.0
10	100.0	98.0	85.0	60.0	35.0	5.0	2.5
11	100.0	100.0	100.0	75.0	50.0	25.0	5.0
12	100.0	100.0	95.0	70.0	45.0	20.0	5.0
13	100.0	100.0	90.0	65.0	40.0	15.0	5.0
14	100.0	98.0	98.0	60.0	35.0	10.0	2.5
15	100.0	98.0	85.0	75.0	35.0	10.0	2.5
16	100.0	98.0	85.0	60.0	50.0	10.0	2.5
17	100.0	91.5	91.5	45.0	22.5	5.0	2.5
18	100.0	91.5	72.5	72.5	22.5	5.0	2.5
19	100.0	91.5	72.5	45.0	45.0	5.0	2.5
20	100.0	98.0	90.0	70.0	40.0	5.0	2.5
21	100.0	98.0	95.0	60.0	30.0	0.0	0.0
22	100.0	85.0	70.0	70.0	45.0	5.0	2.5
23	100.0	98.0	95.0	85.0	60.0	5.0	2.5
24	100.0	70.0	45.0	15.0	0.0	0.0	0.0
25	100.0	75.0	50.0	20.0	5.0	0.0	0.0
26	100.0	80.0	55.0	25.0	10.0	0.0	0.0
27	100.0	85.0	30.0	30.0	10.0	0.0	0.0
28	100.0	85.0	60.0	15.0	10.0	0.0	0.0
29	100.0	85.0	60.0	30.0	0.0	0.0	0.0
30	100.0	91.5	45.0	45.0	22.5	5.0	2.5
31	100.0	91.5	72.5	22.5	22.5	5.0	0.0
32	100.0	91.5	72.5	45.0	0.0	0.0	0.0
33	100.0	100.0	45.0	45.0	45.0	5.0	2.5

obtained by ISHC sampling would be expected to exceed the No. 5 grading limits. This is comparable to the twenty percent found by Fletcher and Mills [11].

CONCRETE MIX AND MATERIALS

Coarse Aggregate

All material comprising the coarse aggregate component, except that passing the No. 8 sieve, was hard, round to subangular gravel of glaciofluvial origin from a single stockpile which met ISHC requirements for No. 5 concrete aggregate. The same natural sand used as fine aggregate was used as the No. 8 to pan fraction of the coarse aggregate. The physical properties of the coarse aggregate are given in Table 5.

TABLE 5

PHYSICAL PROPERTIES OF AGGREGATES

Coarse Aggregate	
Specific Gravity (BSSD):	2.62
Absorption, percent:	1.3
Fine Aggregate	
Specific Gravity (Bulk):	2.6
Absorption, percent:	1.6
Fineness Modulus:	2.91

Fine Aggregate

The fine aggregate used throughout the investigation was natural sand of glaciofluvial origin from a single stockpile which met the ISHC requirements for No. 14-2 concrete aggregate. The physical properties of the fine aggregate are given in Table 5.

Cement

Type I portland cement conforming to ASTM Designation: C150-72 (ASTM C150), Standard Specifications for Cement, from a single clinker batch was used throughout the investigation. The laboratory designation of this cement was No. 322. The physical and chemical properties of the cement are given in Table 6.

Air Entraining Admixture

Vinsol resin from a single supplier delivery was used throughout the investigation.

Concrete Mix

All characteristics and quantities of the materials, except for the size distribution of the coarse aggregate, were the same, insofar as possible, for all concrete batches. The concrete mixture used throughout the investigation was designed in accordance with the following ISHC criteria:

TABLE 6

PHYSICAL AND CHEMICAL PROPERTIES OF CEMENT 322

Physical Properties

Fineness, No. 325 sieve	84.1 percent
Specific surface, Blaine	3720 sq.cm/gm.
Initial set	2 hr. 30 min.
Final set	4 hr. 15 min.
Air entrained (ASTM Designation: C185)	8.5 percent

Chemical Analysis

Compound	Percentage
Silicon dioxide, SiO_2	21.42
Aluminum oxide, Al_2O_3	5.68
Ferric oxide, Fe_2O_3	2.34
Calcium oxide, CaO	64.41
Magnesium oxide, MgO	1.07
Sulphur trioxide, SO_3	2.84
Ignition loss	1.22
Total Alkalies as Na_2O	0.65
Insoluble Residue	0.24

Calculated Compound Composition

Compound	Percentage
Tricalcium Silicate, C_3S	49.9
Dicalcium Silicate, C_2S	23.9
Tricalcium Aluminate, C_3A	11.1
Tetracalcium Aluminoferrite, C_4AF	7.1

Cement content - 6 ± 2% sacks per cubic yard

Maximum water content - 5.5 gallons per sack of cement

Slump - 1/2 to 2 inches

Air entrainment - 5 to 7%

Quantity of fine aggregate - 38% of total aggregate by weight.

The mix proportions which satisfied the above criteria are shown in Table 7. They were established by adjusting the proportions of trial batches, which contained the norm grading, until a 1 1/4 inch slump and six percent air content were obtained. The seven batches made with the norm grading during the testing portion of the investigation had an average slump of 1 1/4 inch. The 28-day compressive strength for two specimens having the norm grading averaged 4780 psi. One specimen having the norm grading was examined microscopically and found to have approximately six percent air content.

TABLE 7

MIX PROPORTIONS FOR ALL BATCHES TESTED

Component	Quantity per Cy	Quantity per Batch
Fine aggregate	1200 lbs (dry)	40 lbs (dry)
Coarse aggregate	1950 lbs (dry)	65 lbs (dry)
Cement	564 lbs	18.8 lbs
Water		
Absorbed	8.5 lbs	0.3 lbs
Free	246.5 lbs	8.2 lbs
Total	255.0 lbs	8.5 lbs
Air Entraining		
Admixture	300 ml	10 ml

PROCEDURES

The details of the procedures used in storing the cement, preparing the aggregates, and mixing and testing the concrete are given in this section.

Cement Storage

The cement was stored in delivery sacks within a low humidity, constant temperature storage room.

Aggregate Preparation

All aggregates were oven dried to a moisture content which did not exceed five percent of the saturated surface dry moisture content. After drying, the aggregates were separated into the desired size ranges with a Gilson vibrating separator and stored in the laboratory. The coarse aggregate, obtained from a stockpile of No. 5 gravel, was separated into the fractions specified by the ISHC No. 5 concrete aggregate grading series, except for the material passing the No. 8 sieve which was not used. Sand, obtained from a stockpile of No. 14-2 fine aggregate, was either scalped at the No. 8 sieve or separated at the No. 4 and No. 16 sieve. The material retained on the No. 8 sieve in the former case and on the No. 4 in the latter was not used. Sand passing the No. 8 was used as the No. 8 to pan fraction

in the coarse aggregate. The No. 4 to No. 16 and No. 16 to pan fractions of sand were recombined as the fine aggregate component of the mix.

Mixing and Testing

Five batches of concrete per day were mixed over a period of approximately one month. Each batch of concrete was mixed and tested in the laboratory in accordance with the standardized routine described in this section. The temperature in the laboratory was always between 79°F and 84°F during the mixing.

The several size fractions of coarse aggregate were recombined by weight into the desired grading, the total weight for each batch being 65.0 pounds. This weight and all others in the investigation were measured to the nearest 0.05 pound. The entire coarse aggregate component was immersed in water and soaked for a minimum of eighteen hours. Immediately prior to mixing, enough of the soaking water was drained off to bring the total weight of water and coarse aggregate to 73.5 pounds. This procedure was necessary to reduce erratic absorption of free water during mixing which would cause higher variability within and between batches. The air entraining agent was added to this combination.

The bowl of the mixer, a Lancaster horizontal, counter-revolving type, was "buttered" with a coating of mortar before the first batch mixed each day. The mortar was spread with a rag until the coating was similar to that

remaining in the trowel scraped bowl after each successive batch.

Two fractions of fine aggregate (15 pounds of the No. 4 to No. 16 fraction, 25 pounds of the No. 16 to pan fraction) were entered into the mixer first, along with 18.8 pounds of cement. The sand and cement were dry mixed for one minute after which the water, coarse aggregate and admixture were added. The batch was then mixed for five minutes.

The following measurements were made on the fresh concrete at the time (elapsed time after completion of mixing) indicated: (a) unit weight after compaction by a compacting factor apparatus - 2 minutes, (b) slump - 3 minutes, (c) remolding effort in jigs - 3 1/2 minutes, (d) unit weight after compaction by vibrating for ten seconds - 5 minutes, (e) unit weight after compaction by vibrating for twenty seconds - 7 minutes, and (f) unit weight after compaction by rodding - 10 minutes.

The compacting factor apparatus, Figure 9, was used as prescribed by British Standard 1881, except that the concrete had to be forced out of each hopper by slight rodding. Immediately after the compacting factor cylinder was weighed, the concrete in the cylinder was compacted further by slowly inserting and withdrawing a 3/4 inch diameter by one foot long immersion, poker vibrator over a ten second period. The vibrator was a small WYCO (Series 900) Model made for narrow concrete sections. A truncated conical hopper was

FIGURE 9. COMPACTING FACTOR APPARATUS

placed on top of the cylinder, Figure 10, and partially filled to provide the additional concrete needed to keep the cylinder full during vibration. The compacting factor cylinder was again struck off and weighed after the ten seconds of vibration.

A slump test (ASTM C143) was made by placing the cone inside the remolding apparatus, Figure 11. After removing the cone and measuring the slump to the nearest 1/4 inch a remolding test [5] was performed. The concrete used for the slump and remolding tests plus a small amount from the mixer was scooped into a six inch diameter by twelve inch long paperboard cylinder mold (ASTM C470) with the conical hopper placed on top. The specimen was compacted by vibrating the concrete with the immersion vibrator in the same manner as for the ten second procedure only over a period of twenty seconds.

Two more cylindrical specimens were made with the concrete remaining in the mixer. They were compacted in paperboard molds by the standard rodding procedures described by ASTM C192, struck off and then weighed.

All specimens compacted in paperboard molds were cured in accordance with ASTM C192, except for a few which were examined for segregation and air content or used for book ends. Two of the cured specimens having the norm grading were tested for 28-day compressive strength. All others were broken at seven days in accordance with ASTM C39.

FIGURE 10. COMPACTING FACTOR CYLINDER
WITH HOPPER AND POKER VIBRATOR

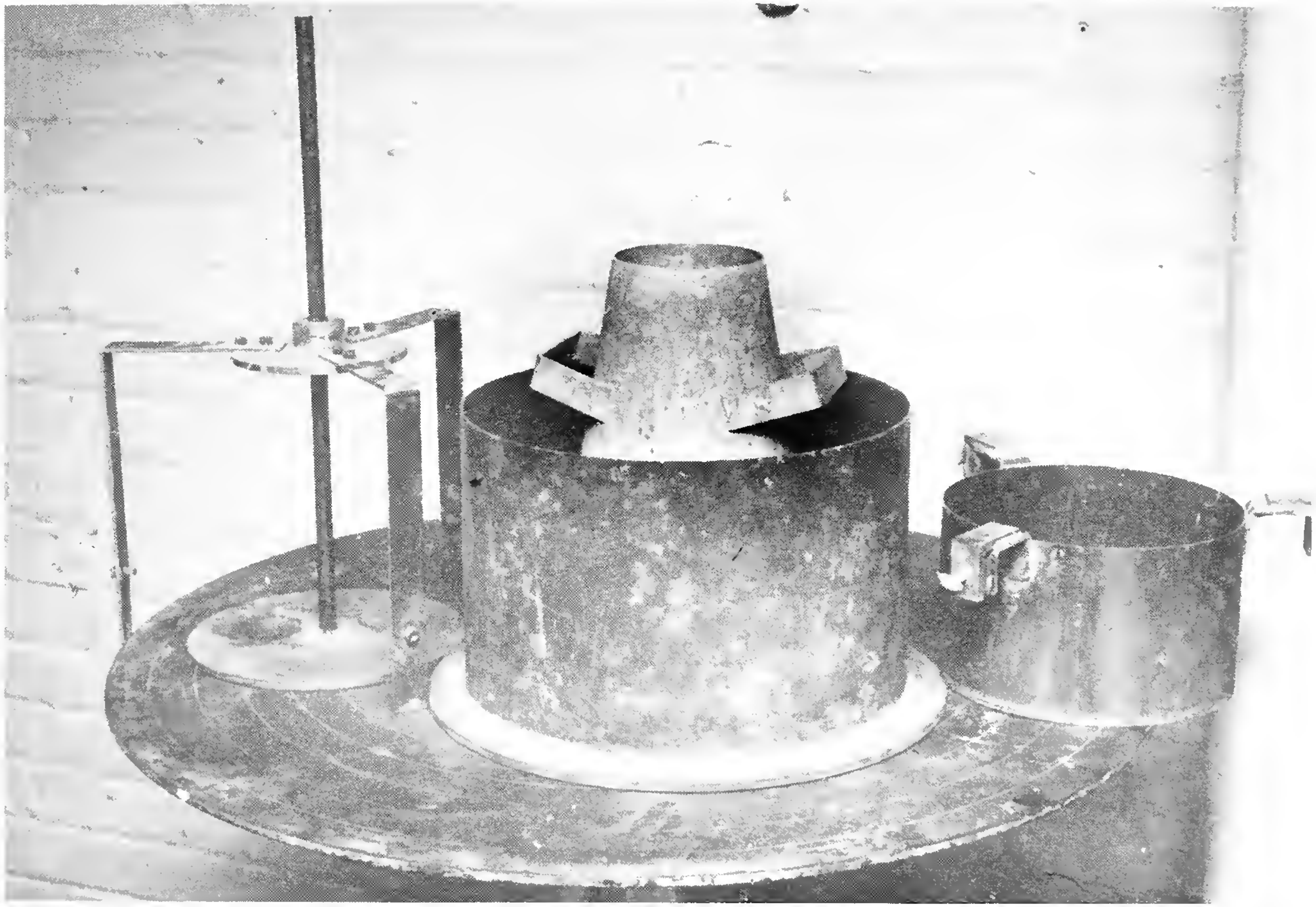

FIGURE 11. REMOLDING APPARATUS PARTS WITH SLUMP CONE

If a batch was seen to bleed excessively during the twenty seconds of vibration, the specimen was later sawed and visually examined for segregation. Five of the specimens made by twenty seconds of vibration were also sawed and examined for air content by the microscopic point count method described in ASTM C457.

PRESENTATION AND DISCUSSION OF RESULTS OF LABORATORY TESTS

The presentation and discussion of results make frequent reference to the fineness index of each coarse aggregate grading. The index is comparable to the fineness modulus (ASTM C125) commonly used to describe the relative fineness of fine aggregate gradings. The fineness index was calculated as $\Sigma r_i/100$, where r_i equals the cumulative percentage retained on the individual sieves in the ISHC No. 5 gradation series, except for the No. 200 sieve. Table 8 shows the calculation of the fineness index for the norm grading. The terms "fine" and "coarse" in regard to grading are relative classifications on the basis of fineness index, finer gradings having lower indices than coarses gradings. It should also be noted that the surface area of the coarse aggregate is inversely proportional to the fineness index; thus the finer gradings have more surface area.

The various components of the variance associated with concrete production are discussed throughout this section. The term "overall" as used herein refers to the combination of testing, sampling and actual variation of the material

TABLE 8

CALCULATION OF FINENESS INDEX FOR THE NORM GRADING

Sieve Size	Percent Passing	Percent Retained	Cumulative Percent Retained
1 1/2 in.	100.00	0.00	0.00
1 in.	91.50	8.50	8.50
3/4 in.	72.50	19.00	27.50
1/2 in.	45.00	27.50	55.00
3/8 in.	22.50	22.50	77.50
No. 4	5.00	17.50	95.00
No. 8	2.50	2.50	97.50
			Σ = 361.00

Fineness Index = 361/100 = 3.61

property being discussed. The term "testing" refers to the combined sampling and testing variation.

The coarse aggregate gradings taken as a group represent gradation variability within the basic concrete mixture and the results are often discussed in terms of the effect of gradation variability.

The grading numbers used to identify gradings refer to those listed in Table 4 of the section: Selection of Gradings Investigated.

This section includes tables of average results only; complete tabulation of all test results is presented in the Appendix.

Results of Slump Tests

The average result for each grading is listed in Table 9. Figures 12 - 18 show the average slump associated with percent passing curves for gradings of major interest.

Homogeneity of variance among the test results was accepted after evaluating the data by the Foster-Burr test [15]. ANOV 1 (Analysis of Variance No. 1), Table 10, showed the variation in slump, which resulted from the entire set of gradings examined, to be significant. Figure 19 shows the average slump plotted versus the fineness index for each grading examined. The plot suggests a general trend of increased slump over the entire range from finer to coarser gradings. A simple linear regression of slump on fineness was found to be significant. The ANOV is included in the Appendix as Table 31. The analysis statistically substantiates the observable trend of increased slump with decreased fineness over the range of gradings examined. It is not intended to imply that the relationship is best defined as simple linear, but rather that in general finer gradings resulted in lower slump.

The following observations were made from examination of the average results:

1. Variation of the smaller sizes of aggregate seemed to have a greater effect on slump than similar variation of larger sizes.

TABLE 9

AVERAGE RESULTS OF SLUMP TESTS

Grading No.	Fineness Index	Number of Tests (Batches)	Average Slump In.
1	3.61	7	1.29
2	3.09	2	1.00
3	4.15	2	1.88
4	3.47	1	1.25
5	3.72	1	1.75
6	3.98	1	1.75
7	3.56	1	0.50
8	3.69	3	1.58
9	3.70	1	1.75
10	3.14	2	1.25
11	2.45	3	0.75
12	2.65	1	0.50
13	2.85	3	1.00
14	2.96	3	1.25
15	2.94	3	1.00
16	2.94	3	0.75
17	3.42	3	1.17
18	3.33	3	1.58
19	3.38	1	1.00
20	2.94	2	0.75
21	3.17	1	1.00
22	3.22	1	1.00
23	2.55	1	0.25
24	4.70	3	1.75
25	4.50	1	1.50
26	4.30	3	2.33
27	4.30	3	1.92
28	4.30	3	1.67
29	4.25	3	1.58
30	3.88	2	1.38
31	3.86	2	1.38
32	3.91	3	1.75
33	3.58	1	1.50

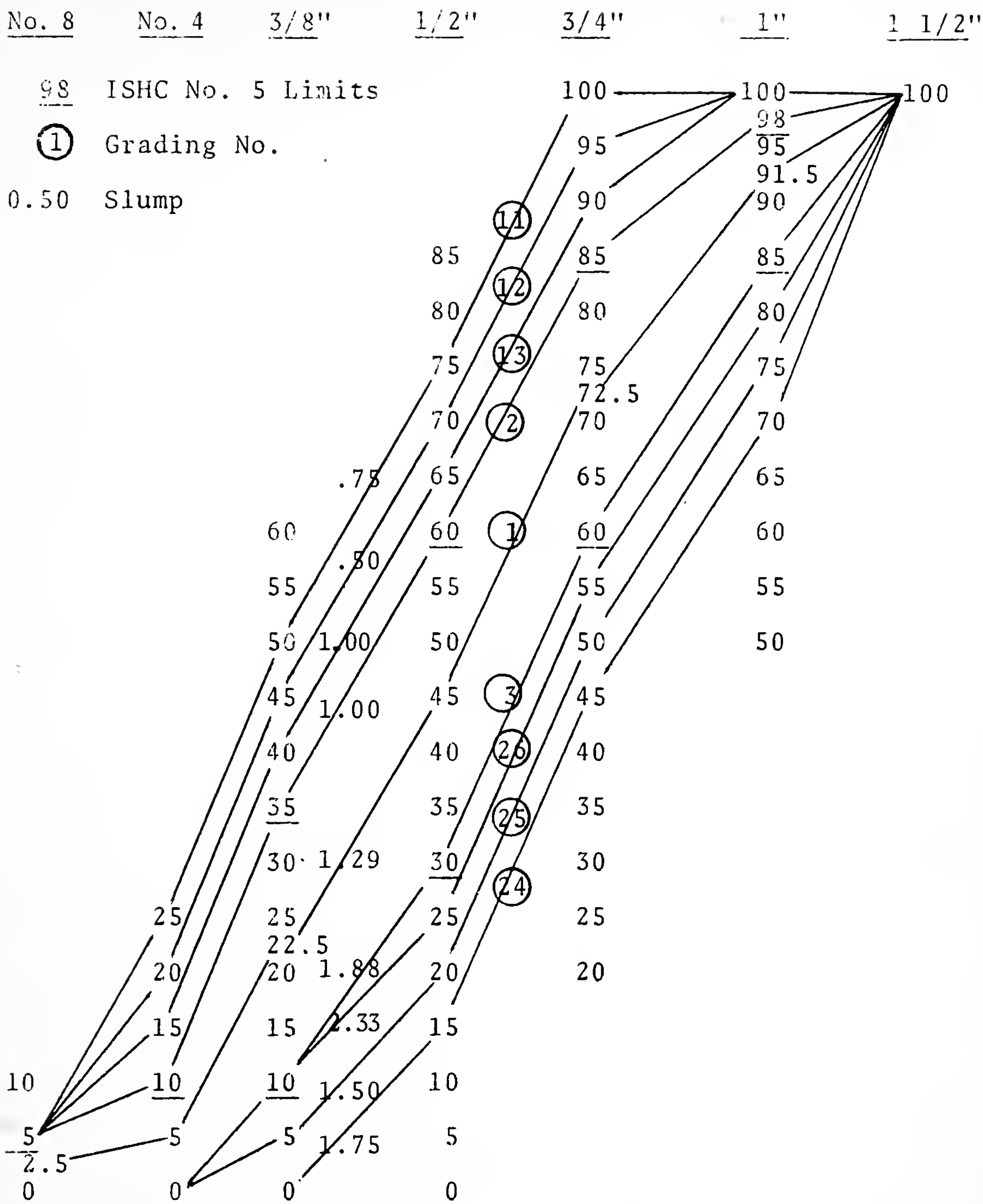

FIGURE 12. AVERAGE SLUMP RESULTS FOR GRADINGS

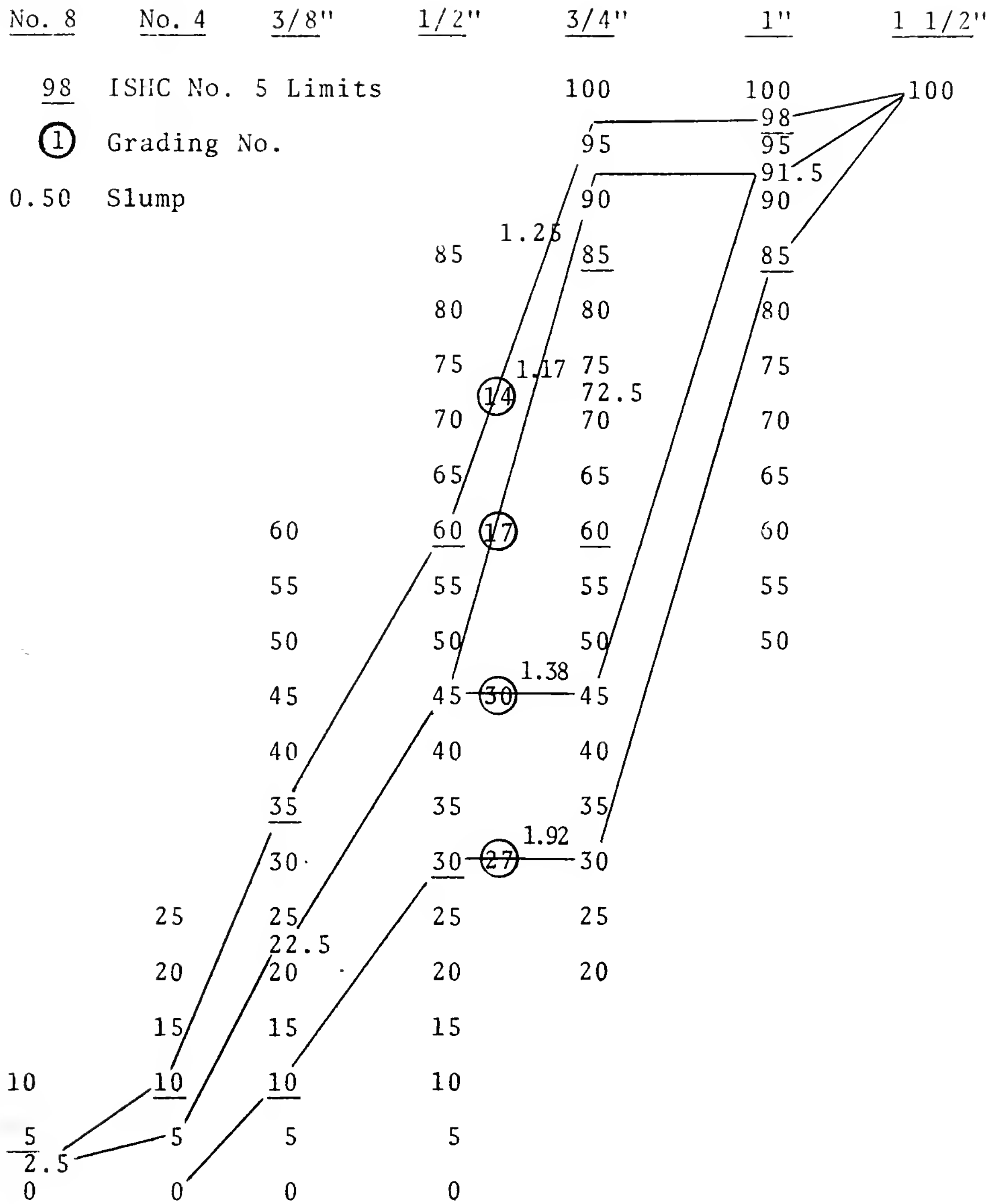

FIGURE 13. AVERAGE SLUMP RESULTS FOR GRADINGS

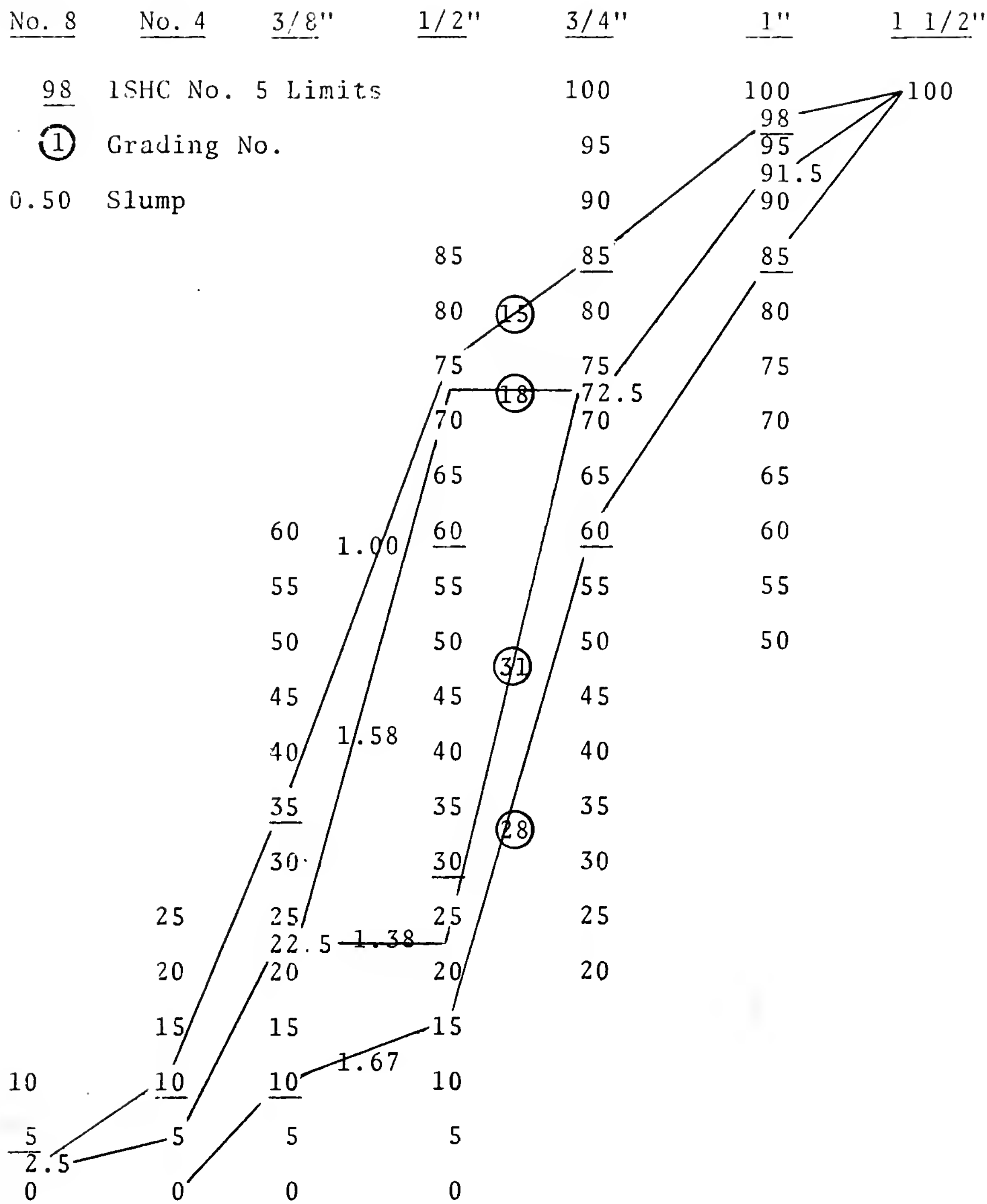

FIGURE 14. AVERAGE SLUMP RESULTS FOR GRADINGS

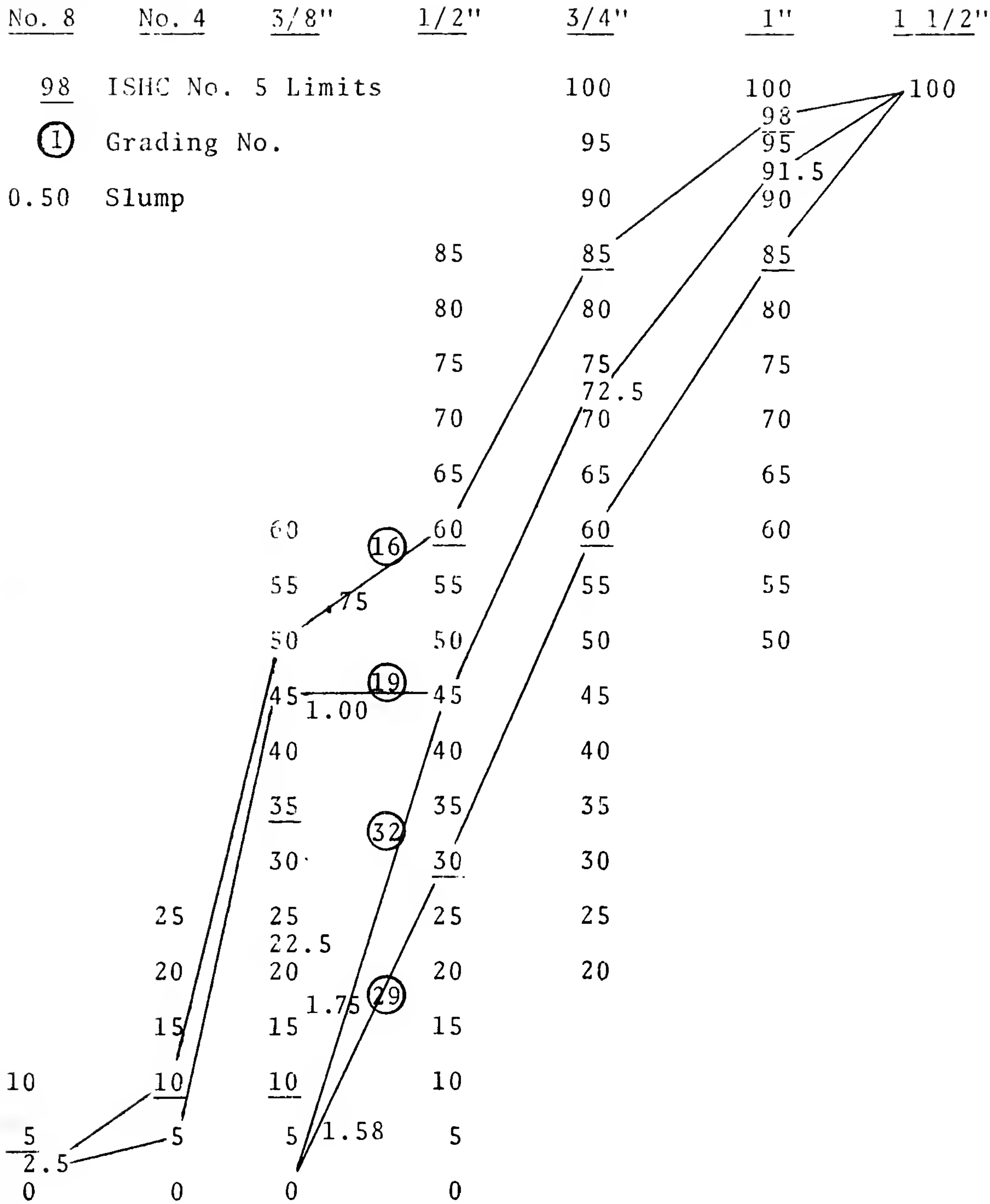

FIGURE 15. AVERAGE SLUMP RESULTS FOR GRADINGS

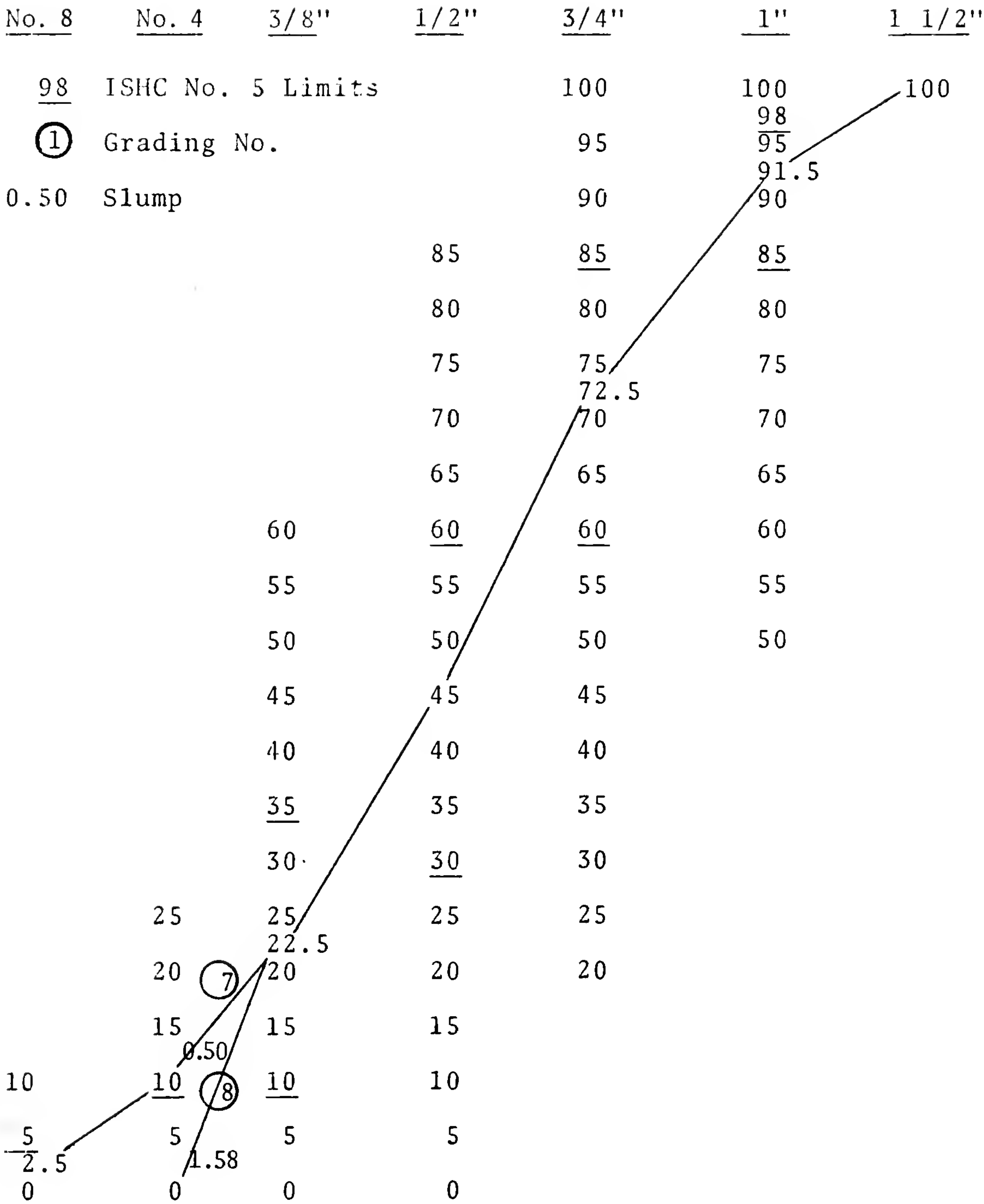

FIGURE 16. AVERAGE SLUMP RESULTS FOR GRADINGS

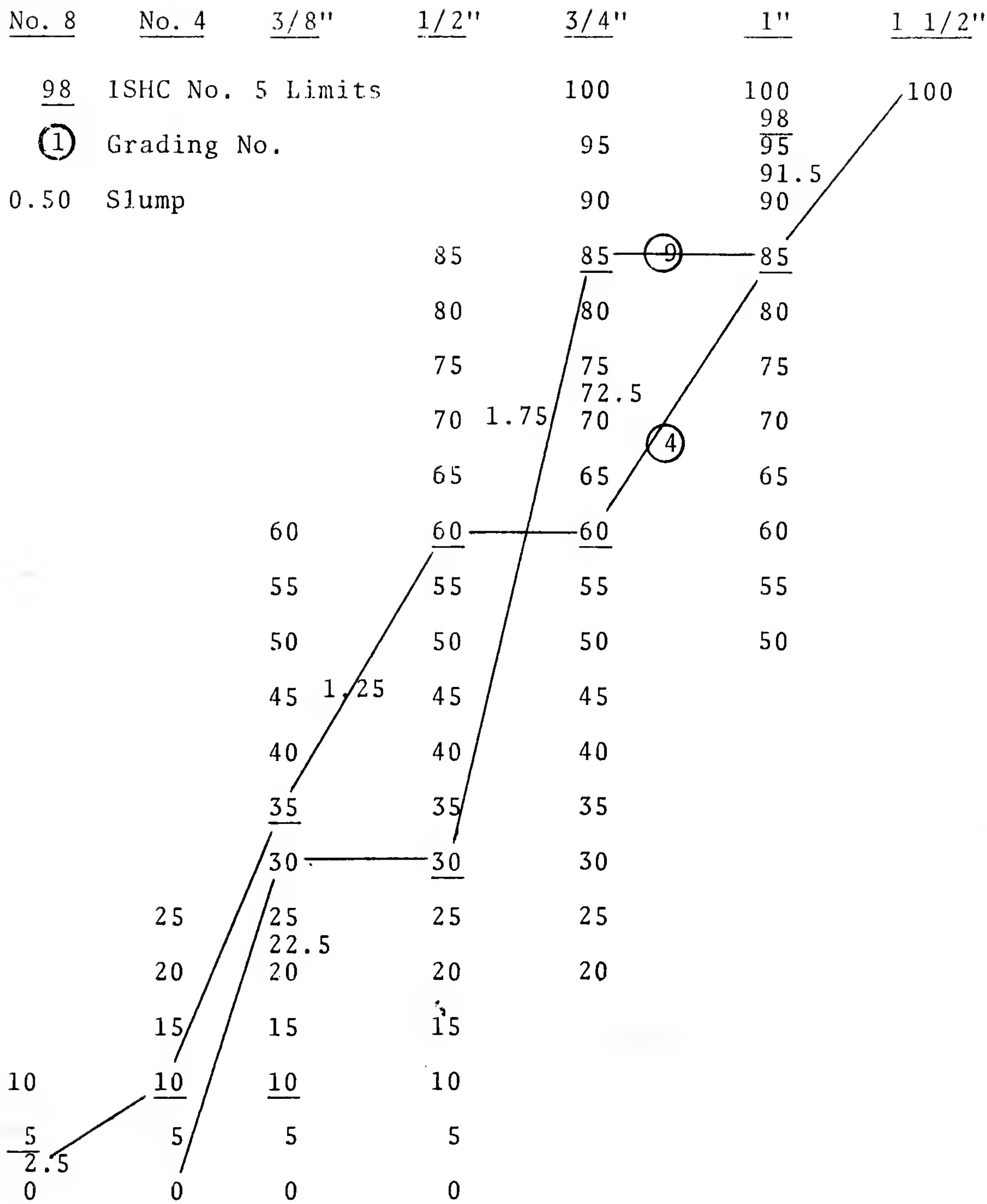

FIGURE 17. AVERAGE SLUMP RESULTS FOR GRADINGS

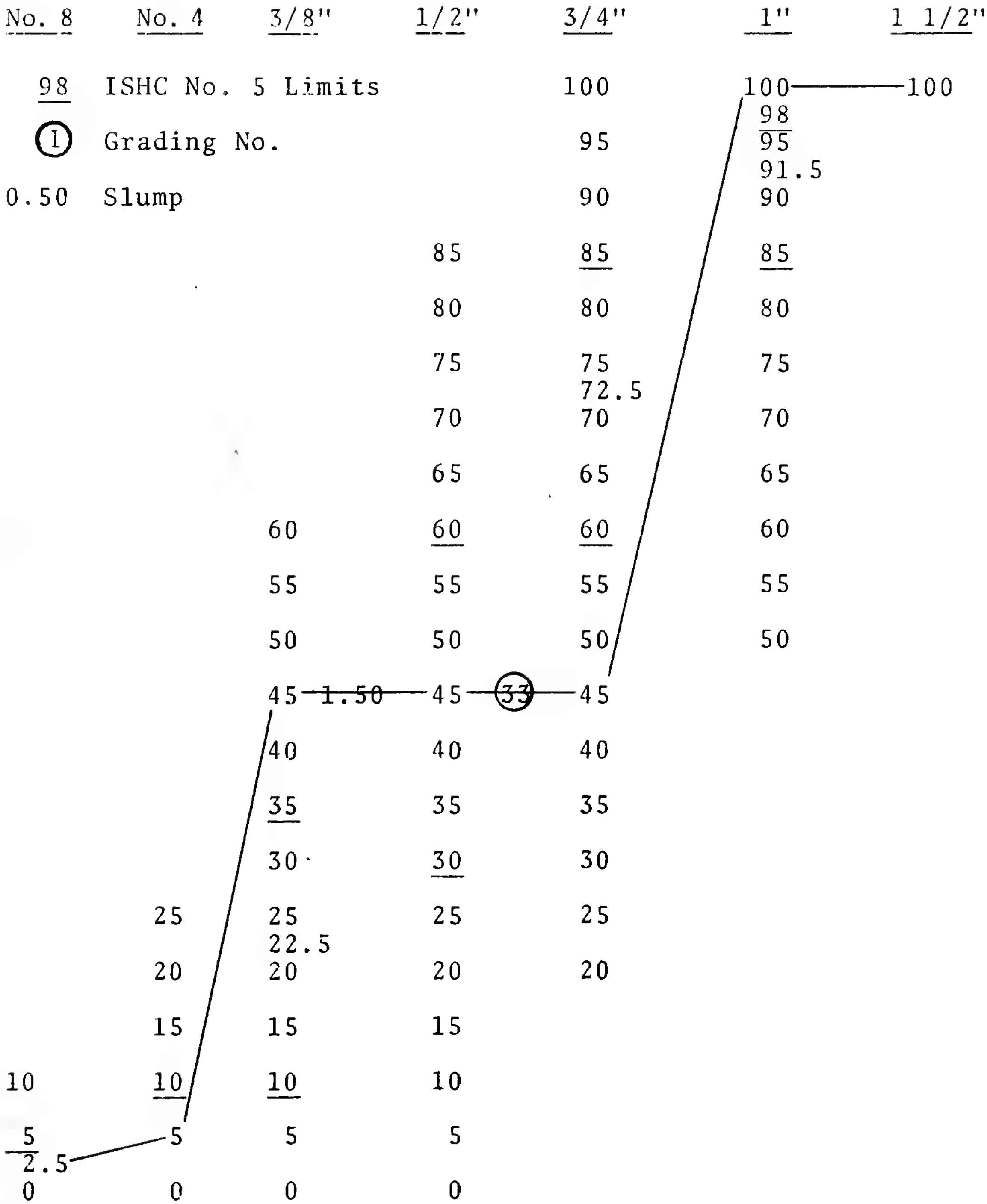

FIGURE 18. AVERAGE SLUMP RESULTS FOR GRADINGS

TABLE 10

ANOV 1 - ANALYSIS OF VARIANCE, SLUMP

Source of Variation	df	SS	MS	EMS	F	F(.05)
Gradation	32	13.7648	0.4301	$\sigma_t^2 + 2.2\ \sigma_g^2$	5.62*	1.73
Error	40	3.0640	0.0766	σ_t^2		
				$\hat{\sigma}_g^2 = 0.16$		

* Significant

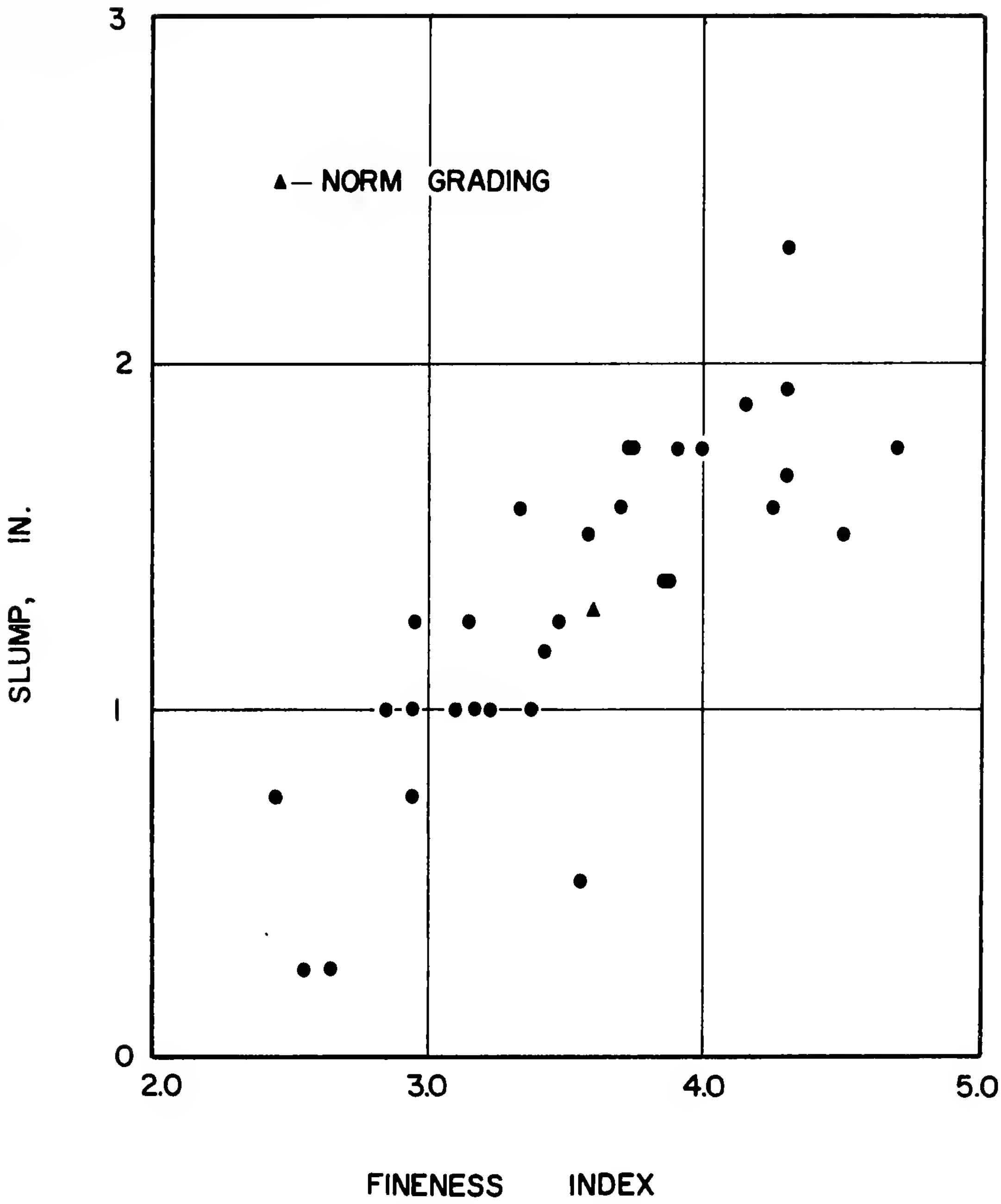

FIGURE 19. AVERAGE SLUMP VS. FINENESS OF COARSE AGGREGATE GRADING

2. The average result for each grading within the ISHC No. 5 limits did not exceed the 1/2 to 2 inch specification requirement.
3. Gap gradings did not seem to affect slump differently than continuous gradings having approximately the same fineness index.

The variance $\hat{\sigma}_g^2$ from ANOV 1, Table 10, provides a quantitative measure of the effect of gradation which is more meaningful than the individual slump result for each grading. $\hat{\sigma}_g^2$ is the variance in slump caused solely by the various gradings examined during the investigation. The entire set of gradings represents the variation in gradation which occurs on typical highway projects, and so $\hat{\sigma}_g^2$ can be considered representative of the variance in slump which results from the variation in gradation in typical highway concrete production. In order to use $\hat{\sigma}_g^2$ in this manner it is necessary to assume that the batch to batch variations have been minimized by the procedures used in the laboratory. ANOV's for other data which allowed evaluation of batch to batch variation showed batches to be significant, but this should not detract from the understanding that the degree of control maintained on the materials and mixing could not be matched in the field or reduced, to any great extent, by methods other than used. Thus, $\hat{\sigma}_g^2$ was taken as a maximum variance which could be observed above a reasonably minimized batch to batch variance.

As mentioned previously, the variation in slump for typical highway concrete has been measured. Table 11 shows the standard deviations for material, s_a, of the slump test results from a study by Hanna, McLaughlin and Lott [16]. The study involved field tests of highway concrete being produced under contract for the ISHC. The testing plan was conducted so as to identify and separate the testing and actual material variation. The portion of the actual material variation which can be attributed to variation in gradation can be calculated as follows:

$$(\hat{\sigma}_g^2/s_a^2) \times 100 \qquad [17].$$

In making this calculation the gradation variability represented by the gradings examined in this laboratory investigation is assumed to characterize that same factor in the statistical model for the field studies. Thus, differences in type of coarse aggregate, type of production equipment and mean slump are not considered.

The values of s_a^2 and $\hat{\sigma}_g^2$ are of course estimates, and any comparison of them provides only a means of evaluating the relative importance of coarse aggregate gradation variability. It should also be reemphasized that $\hat{\sigma}_g^2$ is the result of conservative estimates of the $\pm$ 3σ variation (i.e. actual gradation variability should not be greater) in gradation which would include 99.7 percent of the gradings occurring in typical production. Using the average standard

TABLE 11

VARIABILITY IN SLUMP OF ISHC PAVING CONCRETE

(After Hanna, McLaughlin and Lott [16])

Site	Material Standard Deviation (s_a), in.	Testing Standard Deviation (s_t), in.
1	1.12	0.48
2	0.75	0.34
3	1.01	0.27
Average	0.96	0.36

deviation for slump from Hanna, McLaughlin, and Lott's study of Indiana projects:

$$(\hat{\sigma}_g^2/s_a^2) \times 100 = (0.16/0.92) \times 100 = 17\%.$$

Table 12 lists the results of studies by other state agencies which were reported by Newlon [12] and the Federal Highway Administration [14]. The results are for different projects having different types of paving equipment. Though a range in variation would be expected from job to job and state to state, the differences in the reported results are extreme and thus leave in doubt the actual variation one could expect in slump. In a summary statement, Newlon suggested 0.70 inches as an achievable overall standard

TABLE 12

VARIABILITY IN SLUMP OF PAVEMENT CONCRETE

Cited by	Testing Variance (s_t^2), in.^{2}	Sampling Variance (s_s^2), in.^{2}	Material Variance (s_a^2), in.^{2}	Overall Variance (s_o^2), in.^{2}
Newlon [12]				0.25
"				0.64
"				0.36
"				0.16
"				0.14
"				0.27
"				0.90
"				0.64
"	0.10			
FHA [14]	0.16	0.04	0.25	0.46
"	0.13	0.02	0.45	0.64
"	0.25	0.09	0.46	0.79
"	0.07	0.00	0.15	0.22
"	0.08	0.02	0.42	0.53
"	0.03	0.03	0.14	0.21
"	0.08	0.09	0.20	0.38
"	0.16	0.05	0.50	0.71

deviation and 0.50 as desirable. Using these values to evaluate the importance of gradation variability:

$$\text{Achievable control:} \quad \hat{\sigma}_g^2/s_o^2 \times 100 = (0.16/0.49) = 33\%$$

$$\text{Desirable control:} \quad \hat{\sigma}_g^2/s_o^2 \times 100 = (0.16/0.25) = 64\%.$$

The results showed slump to be significantly affected by variation in the grading of natural gravel. This is consistent with accepted principles regarding the relationship of gradation and workability. However, gradation variability may or may not be important to the overall variation of slump depending on the magnitude of variability associated with the production. For the production conditions evaluated by Hanna, McLaughlin and Lott, variability in the grading of natural gravel would be of minor importance to overall slump variation. In the opinion of the author, gradation would become the predominate source of variation only in the case of abnormally tight control. In general, it is evident the combined effect of sources of variation other than coarse aggregate grading is a prominent factor in slump variation, and a tight gradation specification for natural gravel would not itself ensure adequate control of slump variability.

Results of Unit Weight Tests on Specimens Made by Rodding

The average result for each grading is listed in Table 13 along with the fineness index and number of batches.

Homogeneity of variance among the weights for each batch was tested and accepted using the Foster-Burr test. ANOV 2, Table 14, showed batches to be significant and gradation to be not significant. This indicated either no effect of gradation on unit weight or no identifiable effect because of the significantly high batch to batch variance ($\hat{\sigma}_b^2$ = 2.0336). Relating ANOV 2 to a t-test evaluation, $\hat{\sigma}_b^2$ can be used as an estimate of variance for establishing the observable difference in the mean unit weight associated with any two gradings. It can be shown that with three observations (batches) per grading and $\hat{\sigma}_b^2$ equal to 2.0336 a difference of approximately four pounds per cubic foot can be distinguished at a reasonable level of confidence (α = 0.05, β = 0.1). Thus it can be concluded that the unit weights resulting from all the gradings examined did not differ more than approximately four pounds per cubic foot or three percent. A plot of the average results for each grading is shown in Figure 20 included in the section: Results of Unit Weight Tests as a Measure of Compactability.

Hanna, McLaughlin and Lott obtained a testing variance of 1.15 pounds per cubic foot. Comparing this with the testing variance ($\hat{\sigma}_t^2$ = 0.3904) from ANOV 2, the sampling

TABLE 13

AVERAGE RESULTS OF UNIT WEIGHT TESTS

ON SPECIMENS MADE BY RODDING

Grading No.	Fineness Index	Number of Tests	Number of Batches	Average Unit Weight pcf
1	3.61	14	7	148.72
2	3.09	4	2	147.89
3	4.15	4	2	148.47
4	3.47	2	1	149.62
5	3.72	2	1	148.60
6	3.98	2	1	149.23
7	3.56	2	1	148.23
8	3.69	6	3	148.90
9	3.70	2	1	149.24
10	3.14	4	2	148.28
11	2.45	6	3	148.22
12	2.65	2	1	148.21
13	2.86	6	3	148.34
14	2.96	6	3	147.87
15	2.94	6	3	147.36
16	2.94	6	3	147.62
17	3.42	6	3	149.15
18	3.33	6	3	148.05
19	3.38	2	1	149.49
20	2.94	4	2	148.21
21	3.17	2	1	148.34
22	3.22	2	1	148.34
23	2.55	2	1	148.34
24	4.70	6	3	148.94
25	4.50	2	1	150.02
26	4.30	6	3	148.00
27	4.30	6	3	149.87
28	4.30	6	3	148.64
29	4.25	6	3	148.81
30	3.88	4	2	149.55
31	3.86	4	2	148.21
32	3.91	6	3	148.72
33	3.58	2	1	148.85

TABLE 14

ANOV 2 - ANALYSIS OF VARIANCE, UNIT WEIGHT OF RODDED SPECIMENS

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	70.9835	2.2182	1.09	1.73
Batches	40	81.3452	2.0336	5.21*	1.58
Error	73	28.5000	0.3904		

* Significant

and testing procedures of this investigation were seen to be relatively good.

The unit weights were determined from weights of fresh concrete compacted in 6 × 12 inch paperboard cylinder molds (ASTM C470). The size and construction of the container were expected to cause a relatively high testing variance, but the results did not indicate this.

The results are of interest from two aspects: (a) the relationship of unit weight or density to strength and (b) the use of unit weight for evaluating uniformity in the yield. The results showed coarse aggregate gradation variability did not substantially affect the unit weight of the concrete as measured by the standard testing procedure and, as seen in Figure 20, suggest density, if affected at all

by the gradation, to be less for fine gradings. Thus, any effect of density on the strength of the hardened specimens made by rodding should have resulted in lower compressive strength for finer gradings. This result is important to the interpretation of the compressive strengths obtained for these same specimens.

The calculated yield of the concrete mix would vary less than three percent as a result of the maximum variation (four pounds per cubic foot) in unit weight. Thus, gradation variability did not substantially affect the calculated yield for the mixture.

The results are discussed further in regard to compactability in the next section.

Results of Unit Weight Tests as a Measure of Compactability

Four different compactive efforts were applied to the concrete for each batch, and unit weight measurements were made after each effort. The four levels of compactive effort were: (a) dropping through a compacting factor apparatus in accordance with B.S. 1881, (b) ten seconds of vibration with a poker vibrator, (c) rodding in accordance with ASTM C192 and (d) twenty seconds of vibration with a poker vibrator.

The average unit weight resulting from each compactive effort and grading is listed in Table 15 and plotted in Figure 20 versus the fineness index of each grading. The

TABLE 15

AVERAGE RESULTS OF UNIT WEIGHT TESTS, PCF

Grading No.	Fineness Index	20-Sec. Vibration	Rodded Unit Weight	10-Sec. Vibration	Compacting Factor
1	3.61	149.96	148.72	146.03	136.55
2	3.09	150.51	147.89	146.56	135.33
3	4.15	151.28	148.47	146.17	138.01
4	3.47	150.76	149.62	145.92	138.01
5	3.72	150.51	148.60	146.43	136.48
6	3.98	151.28	149.23	147.45	138.01
7	3.56	150.76	149.23	146.43	128.83
8	3.69	151.19	148.89	146.43	137.32
9	3.70	151.02	149.23	146.94	135.71
10	3.14	150.76	148.28	145.92	135.20
11	2.45	149.91	148.21	144.98	130.36
12	2.65	150.00	148.21	146.68	130.36
13	2.85	150.76	148.34	146.85	132.65
14	2.96	150.59	147.87	145.41	134.01
15	2.94	150.68	147.36	146.00	133.67
16	2.94	150.93	147.62	145.58	133.00
17	3.42	150.08	149.15	145.83	134.01
18	3.33	150.17	148.05	145.15	135.37
19	3.38	150.76	149.49	146.94	134.69
20	2.94	150.76	148.21	146.68	132.01
21	3.17	150.76	148.34	145.92	128.57
22	3.22	150.76	148.34	146.17	131.89
23	2.55	150.00	148.34	146.68	128.57
24	4.70	151.19	148.94	147.70	137.92
25	4.50	151.27	151.02	148.47	135.71
26	4.30	150.00	148.00	146.34	139.12
27	4.30	151.19	149.87	147.02	139.11
28	4.30	151.10	148.64	146.51	137.41
29	4.25	150.76	148.81	146.34	136.39
30	3.88	151.78	149.55	146.17	138.52
31	3.86	150.51	148.21	146.43	137.37
32	3.91	149.91	148.72	147.36	136.90
33	3.58	150.76	148.85	146.19	133.42

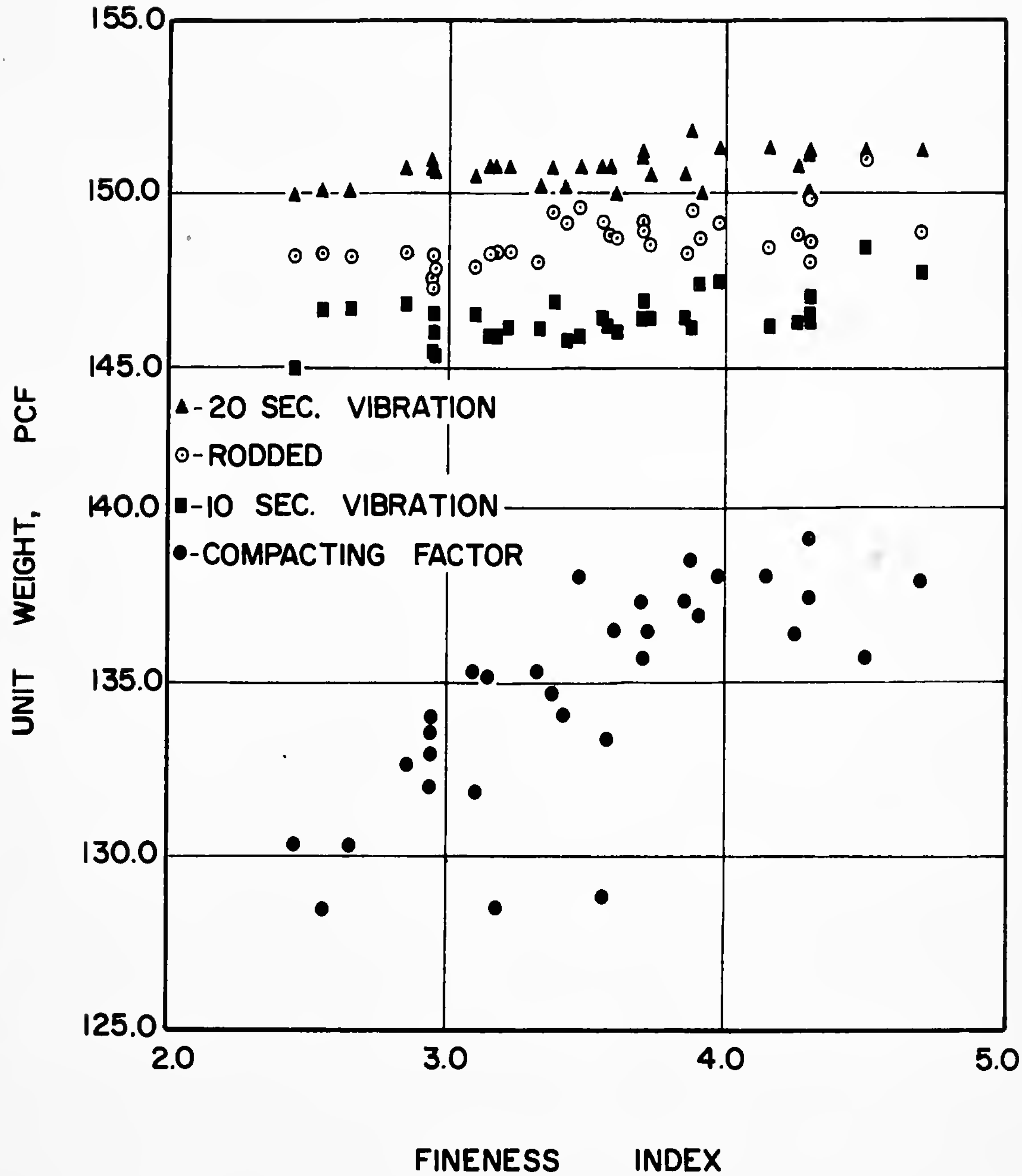

FIGURE 20. AVERAGE UNIT WEIGHT VS. FINENESS OF COARSE AGGREGATE GRADING

ANOV's for the results of each compactive effort are shown in Tables 14 and 16 - 18. The results are discussed in terms of the curves or lines which are defined by the sets of data points shown in Figure 20. (The discussion refers to the slopes of the curves with the knowledge that they may well be curvilinear.)

ANOV's 2, 3, 4 for the last three compacting efforts listed above show grading to be not significant. This indicates the slopes of the upper three lines shown in Figure 20 are not significantly different from zero or, as explained for the rodding effort in the last section, the differences in unit weight are so minimal as to be indistinguishable. The slope of the lower line is shown by ANOV 5 to be significantly greater than zero.

The lower curve shows grading to have affected the workability or compactability of the mix. For the same compaction effort, finer gradings resulted in lower unit weight, indicating more difficulty in densifying or compacting the specimens having finer gradings. This may be attributed to the increased water demand imposed by finer gradings, resulting in a harsher mix.

The effect of grading on compactability is seen to be inconsequential for compaction efforts greater than ten seconds of vibration as indicated by the zero slopes or insignificant differences in unit weights for the upper three curves.

TABLE 16

ANOV 3 - ANALYSIS OF VARIANCE, UNIT WEIGHT AFTER 20 SECONDS OF VIBRATION

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	18.3298	0.5728	0.7553	1.73
Error	40	30.3358	0.7584		

TABLE 17

ANOV 4 - ANALYSIS OF VARIANCE, UNIT WEIGHT AFTER 10 SECONDS OF VIBRATION

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	35.5722	1.1126	1.0215	1.73
Error	40	43.5303	1.0883		

TABLE 18

ANOV 5 - ANALYSIS OF VARIANCE, UNIT WEIGHT FROM COMPACTING FACTOR TEST

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	538.5341	16.8292	4.7447*	1.73
Error	40	141.8792	3.5470		

* Significant

Slopes of curves for compaction efforts between the compacting factor and ten seconds of vibration would be expected to transition from positive to zero. The minimum compactive effort above which the effect of grading becomes inconsequential is left undefined.

A conclusion as to the importance of gradation variability in regard to compactability of field produced concrete rests with one's opinion of the similarity of field vibration to that used in the laboratory. In the opinion of the author the ten seconds of vibration applied to the six inch diameter by twelve inch long specimen by the small poker vibrator was less than normal vibration of slipformed concrete. It was observably less than rodding and substantially less than twenty seconds of vibration, indicating that it is by no means an extreme compactive effort.

The compacting factor test, as well as the slump test previously discussed, showed workability to be significantly affected by variation in the gradation of natural gravel. The knowledge of this relationship and the need to maintain uniform workability are responsible for the traditional practice of specifying coarse aggregate grading limits in concrete production. However, if the ten seconds of vibration are taken as a reasonable representation of field vibration, it can be concluded that from a practical standpoint compactability was not affected by the gradation variability to an extent which caused any substantial

reduction in unit weight. This interpretation of the results suggests that since the gradation variability investigated was so much wider than the ISHC No. 5 limits, the present specification, if adhered to, would be unnecessarily rigid for natural gravel; and it appears quite possible that the present system of controlling gradation, which allows frequent variation outside the limits, has survived because it has been adequate for controlling a noncritical source of variation.

Results of Air Content Determinations

The results of five microscopic air content determinations are presented in Table 19. These tests were made on sections of hardened cylinders which had been compacted by twenty seconds of vibration. Air content appears to have been higher for specimens having finer gradings. Though this observation cannot be statistically substantiated, the results are consistent with the unit weight results. Specimens with finer gradings appear to have had both slightly lower density and slightly higher air content.

Even though the determinations were made on cylinders made by twenty seconds of vibration, the results were considered further evidence that, in regard to density, the strength of the rodded cylinders having finer gradings would be expected to be lower than those with coarser gradings. The parallelism of the unit weight plots of Figure 20

TABLE 19

RESULTS OF MICROSCOPIC AIR CONTENT DETERMINATIONS

Grading No.	Fineness Index	Air Content (% by Volume)
11	2.45	6.1
12	2.65	5.9
1	3.61	5.7
32	3.91	4.9
26	4.30	5.1

suggests that the densities of the rodded cylinders are lower in level only and the relationship of fineness of grading and air content would be the same.

Results of 7-Day Compressive Strength Tests on Cylinders Compacted by Rodding

The average result for each grading is listed in Table 20 along with the fineness index. Figures 21 - 27 show the average strength associated with percent passing curves for gradings of major interest.

Homogeneity of variance among the test results was accepted after evaluating the data by the Foster-Burr test. ANOV 6, Table 21, showed the variation in compressive strength, which resulted from the entire set of gradings examined, to be significant.

TABLE 20

AVERAGE RESULTS OF 7-DAY COMPRESSIVE STRENGTH TESTS ON SPECIMENS MADE BY RODDING

Grading No.	Fineness Index	Number of Tests	Number of Batches	Average Strength psi
1	3.61	5	3	3777
2	3.09	4	2	4266
3	4.15	4	2	3780
4	3.47	2	1	3952
5	3.72	2	1	3838
6	3.98	2	1	3758
7	3.56	2	1	4138
8	3.69	6	3	4038
9	3.70	2	1	3767
10	3.14	4	2	4204
11	2.45	4	2	4717
12	2.65	2	1	4518
13	2.85	5	3	4732
14	2.96	6	3	4265
15	2.94	6	3	4241
16	2.94	6	3	4386
17	3.42	6	3	4141
18	3.33	4	2	3930
19	3.38	2	1	4174
20	2.94	4	2	4633
21	3.17	2	1	4244
22	3.22	2	1	4280
23	2.55	2	1	4518
24	4.70	4	2	3661
25	4.50	2	1	3696
26	4.30	6	3	3434
27	4.30	5	3	3593
28	4.30	4	2	3616
29	4.25	6	3	3640
30	3.88	4	2	3935
31	3.86	2	1	4077
32	3.91	4	2	3577
33	3.58	2	1	3829

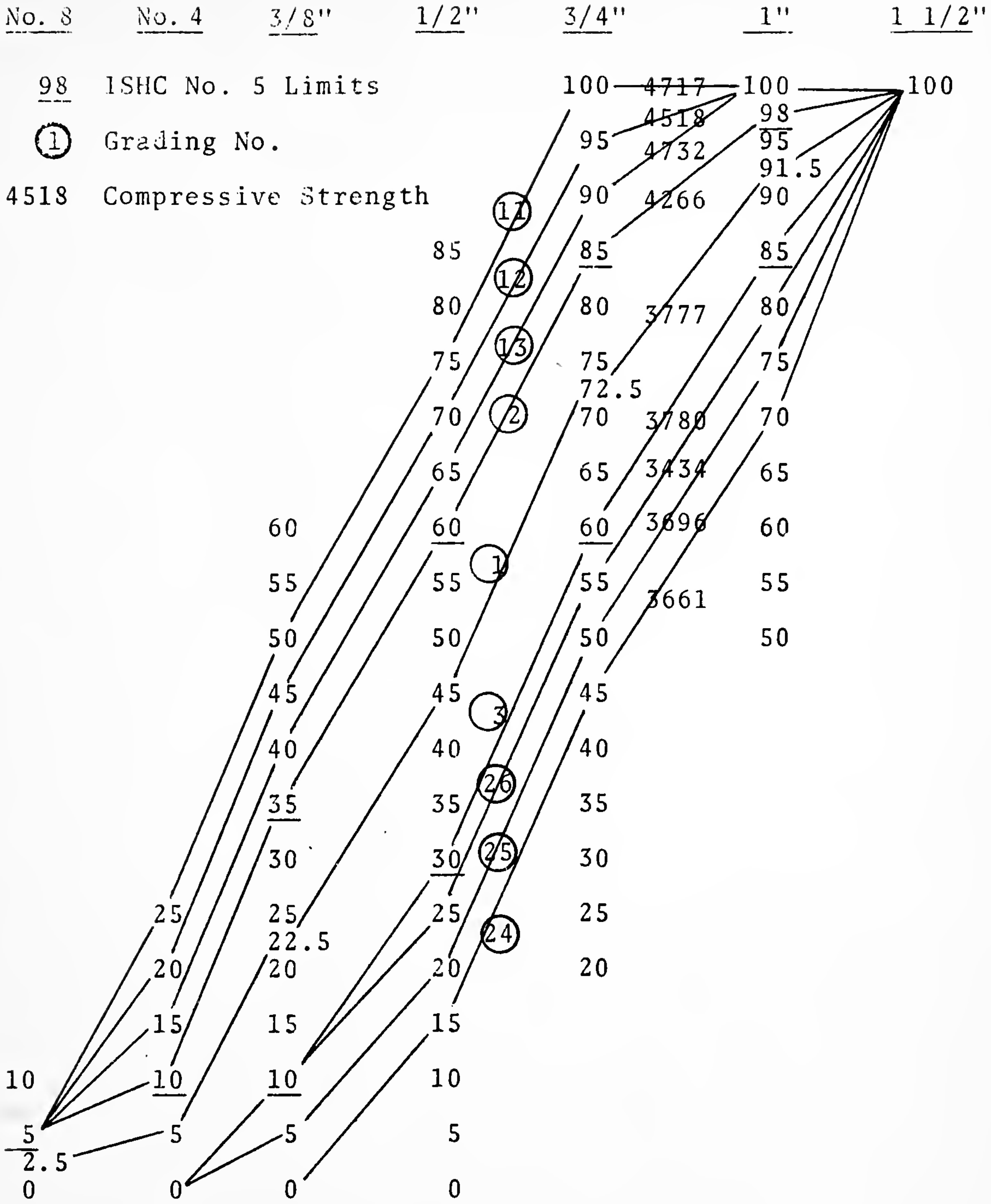

FIGURE 21. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

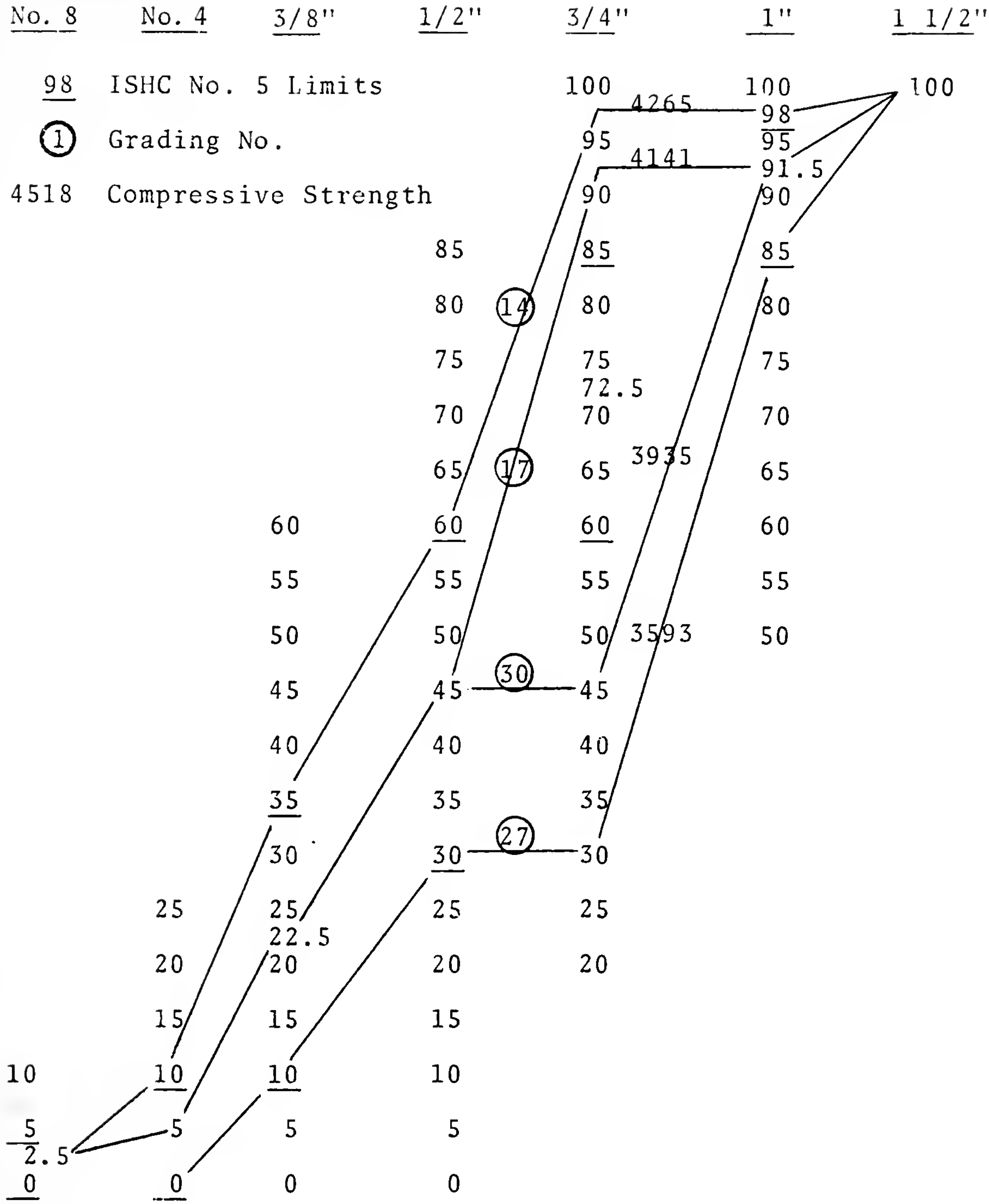

FIGURE 22. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

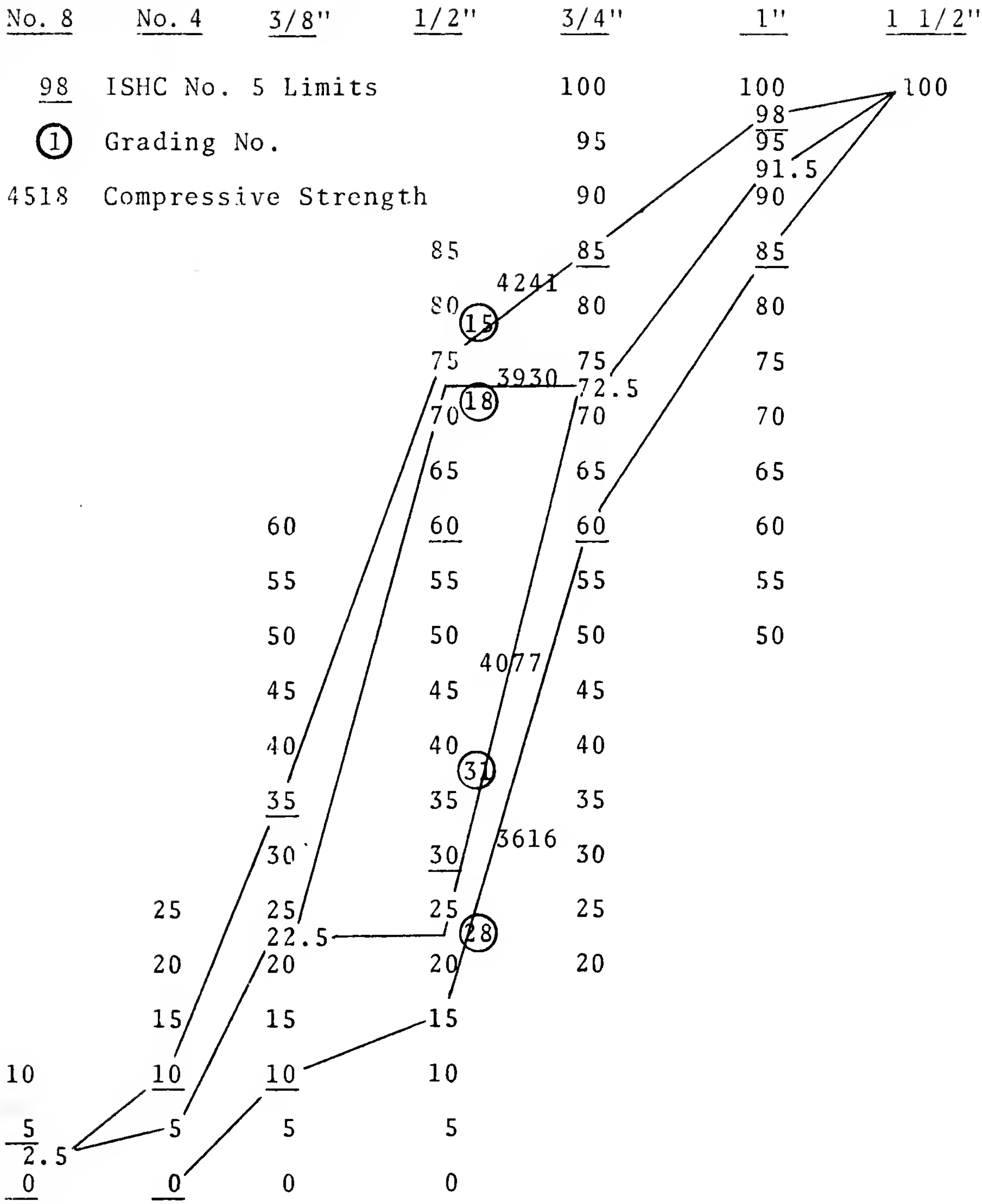

FIGURE 23. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

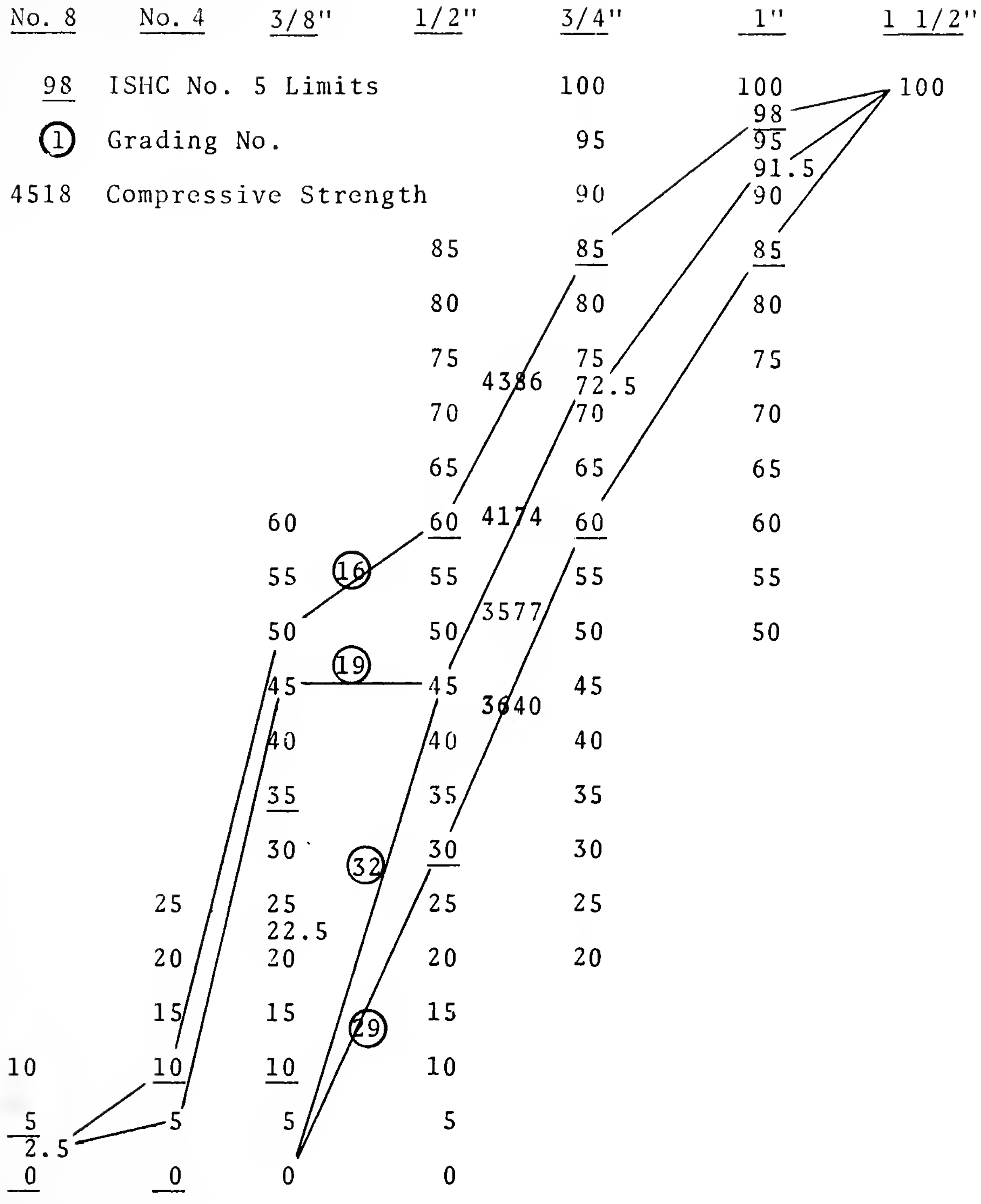

FIGURE 24. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

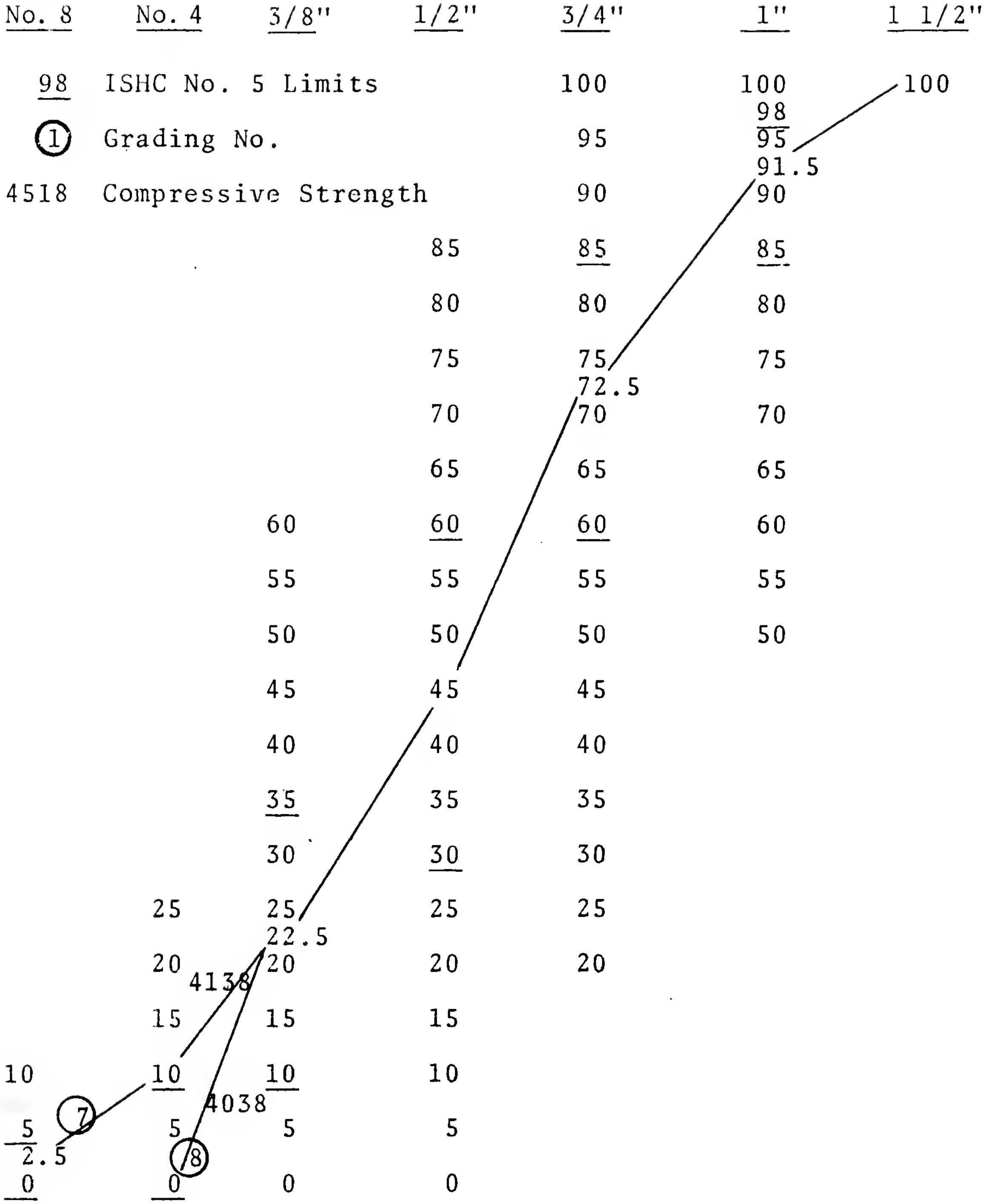

FIGURE 25. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

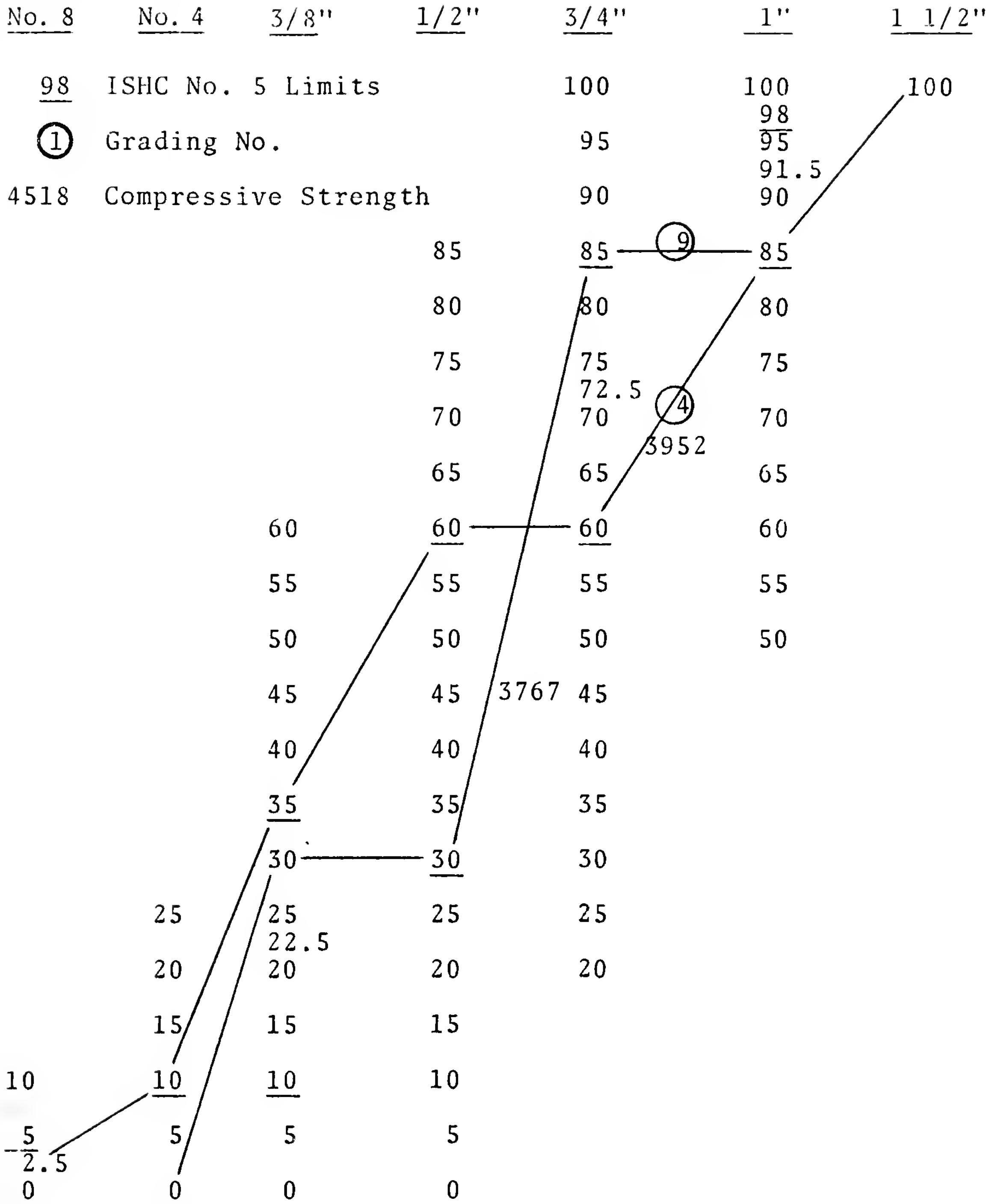

FIGURE 26. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

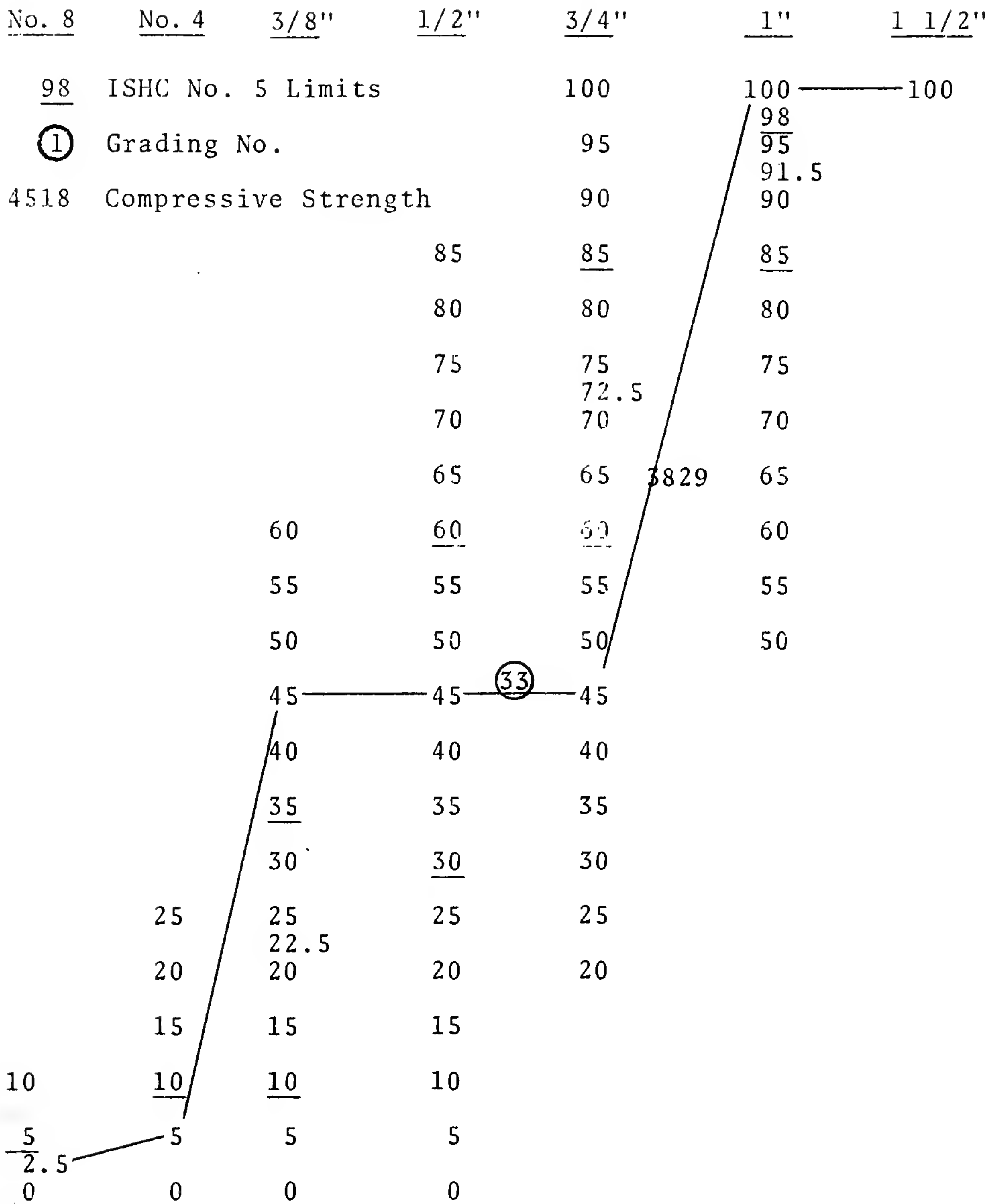

FIGURE 27. AVERAGE COMPRESSIVE STRENGTH RESULTS FOR GRADINGS

TABLE 21

ANOV 6 - ANALYSIS OF VARIANCE, 7-DAY COMPRESSIVE STRENGTH

OF RODDED SPECIMENS

Source of Variation	df	SS	MS	EMS	F	F(.05)
Gradation	32	16,197,795	506,181	$\sigma_t^2 + a\sigma_b^2 + 3.7\sigma_g^2$	4.806*	1.83
Batches	30	3,159,877	105,329	$\sigma_t^2 + a\sigma_b^2$	7.337*	1.65
Error	60	861,377	14,356	σ_t^2		
				$\hat{\sigma}_g^2 = 10.85 \times 10^4$		

* Significant

Figure 28 shows the average strength plotted versus the fineness index of each grading examined. A simple linear regression of strength on fineness index (Table 32, Appendix) was found to be significant. As explained previously in the discussion of slump test results, this analysis provides statistical substantiation of the trend of decreased strength with increased fineness index. Thus, finer grading resulted in higher strength for the range of gradings investigated. It is noted that the higher strength was not attributable, even partially, to higher density, for both unit weight and air content results suggest cylinders having finer gradings to have been less dense.

The following observations were made from examination of the average results:

1. Variation of the smaller sizes of aggregate seemed to have a greater effect on compressive strength than similar variation of larger sizes.
2. The average compressive strength of gap gradings was higher than those of continuous gradings with approximately the same fineness index.
3. In regard to the range in strengths obtained from the various gradings, the decrease in compressive strength from that associated with the norm grading was notably less than the increase.

The observation listed as Item 3 is clarified by Figure 28. Even though the range in fineness index (i.e. the variation

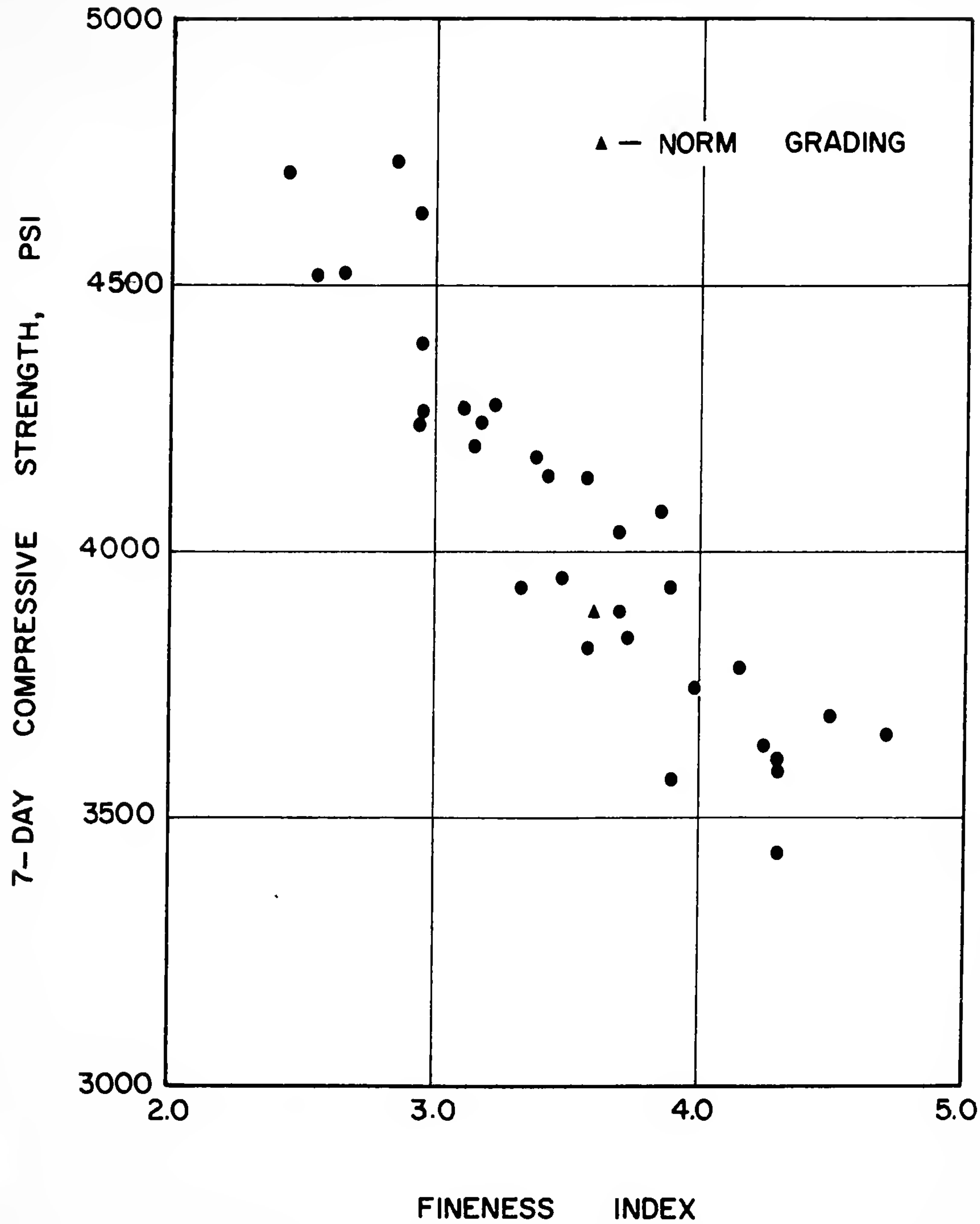

FIGURE 28. AVERAGE COMPRESSIVE STRENGTH OF RODDED SPECIMENS VS. FINENESS OF COARSE AGGREGATE GRADING

in grading) is centered on the norm grading, the strength associated with the norm grading is notably lower than the center of the range of strengths.

As discussed in the section: Results of Slump Tests, $\hat{\sigma}_g^2$ from ANOV 6 can be used to evaluate the portion of actual variation in the compressive strength of field produced paving concrete attributable to variation in coarse aggregate gradation. As was also mentioned in the discussion of slump results, the significance of batch to batch variation ($\hat{\sigma}_b^2$) does not detract from the analysis if it is realized that the laboratory control was maintained at the lowest level practically possible. Statistical studies of paving concrete such as those reported by Newlon have analyzed 28-day compressive strength. Since the data obtained in this investigation were for 7-day strength, it is necessary to assume 7-day and 28-day variations are the same. This assumption has been substantiated by at least one study [18].

Table 22 shows the results of West Virginia research on 28-day compressive strength variations for paving concrete. The standard deviation of interest is s_a for materials. Newlon, in his statistical summary, suggested 500-550 psi as an overall standard deviation, s_o, achievable in normal highway construction, which is in agreement with the average for the West Virginia projects. Using the average of the s_a's from West Virginia's study and $\hat{\sigma}_g^2$ from this investigation: $(\hat{\sigma}_g^2/s_a^2) \times 100 = (10.85 \times 10^4/17.91 \times 10^4) = 61\%$.

TABLE 22

VARIABILITY OF 28-DAY COMPRESSIVE STRENGTH FOR PAVING CONCRETE (after FHA [14])

Project	Testing Standard Deviation (s_t), psi	Material Standard Deviation (s_a), psi	Overall Standard Deviation (s_o), psi
1	377	386	545
2	322	270	420
3	318	495	575
4	200	420	467
5	585	545	733

The degree of importance of gradation depends on the level or amount of overall variation occurring. In this regard it is convenient to evaluate the relationship of $\hat{\sigma}_g^2/s_o^2$ for a range of s_o^2. If production is to be tightly controlled a desirable s_o might be 400 psi, whereas for less critical work a s_o of 700 psi might be acceptable. The relative importance of variation in gradation for these two cases can be seen by comparing $\hat{\sigma}_g^2/s_o^2$:

Good control: $(\hat{\sigma}_g^2/s_o^2) \times 100 = 68\%$

Poor control: $(\hat{\sigma}_g^2/s_o^2) \times 100 = 22\%$.

The compressive strength results, which show strength to be independently related to fineness of coarse aggregate gradation, provide a refined substantiation of the study made by Walker and Bloem [7] which showed strength to be higher for smaller maximum aggregate size. All gradings examined in this investigation, except for the finest continuous gradings, are classifiable within a single maximum size. Thus, it appears that the relationship of coarse aggregate fineness and strength underlies the more conditional relationship established by Walker and Bloem.

The results also suggest that variations in coarse aggregate gradation influence strength test variability more than generally recognized. Even for poorly controlled production, typical variations in natural gravel were seen to be a prominent source of variation in strength.

The distribution of the changes in strength resulting from the grading variations is of particular interest. The gradation variability, which was balanced around the norm grading, resulted in a greater proportion of strength increases than decreases, suggesting that for the mixture and norm grading investigated, gradation variability itself should influence the average strength to be higher than that designed for. Though variation in properties is usually considered detrimental, in this case it provides inherent conservatism.

Interrelationship of Strength, Unit Weight and Fineness of Grading

This section discusses observations made by the author. The results of the investigation provide enough substantiation of certain intuitive relationships to make discussion worthwhile.

The strength of concrete is known to be a function of water-cement ratio, density, and, to some extent, maximum aggregate size. For a given water-cement ratio and maximum aggregate size, strength would be expected to be directly proportional to density. Based on the results of this investigation, a more appropriate statement of the relationship is: for a given water-cement ratio and fineness of coarse aggregate gradation, strength is directly proportional to density.

Figure 29 shows the average compressive strengths of cylinders made with the various gradings plotted against their average unit weights. The data points are plotted as the decimal point of the fineness index for each grading. The data plotted are the results of strength and unit weight tests on specimens made by (1) rodding and (2) vibrating for twenty seconds.

The plot is divided into regions, two of them representing the two compaction efforts. Within each of the two compaction regions, the strength seems to be inversely proportional to density, indicating the fineness of grading influenced strength more than density.

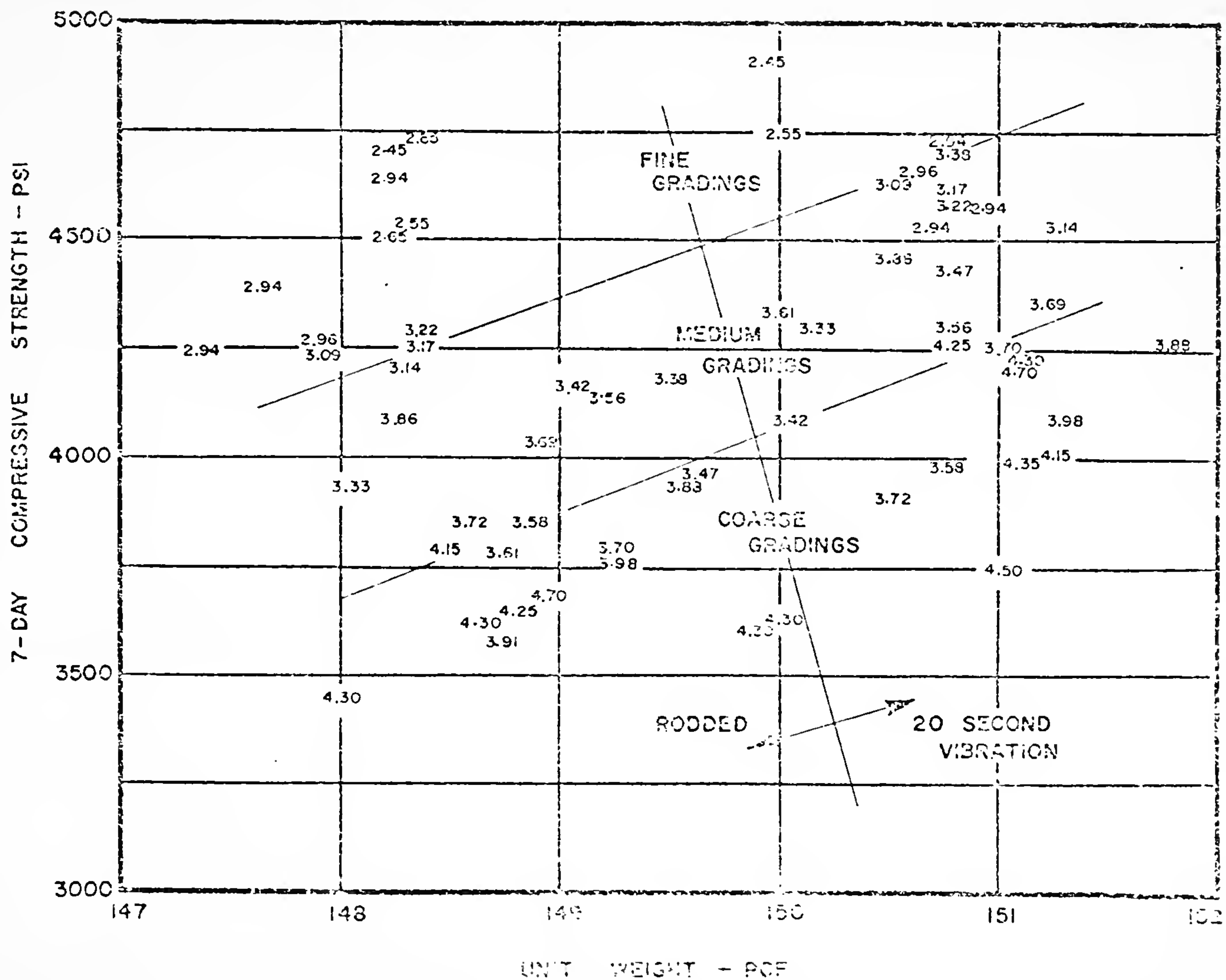

FIGURE 29. COMPRESSIVE STRENGTH VS. UNIT WEIGHT FOR FINENESS OF COARSE AGGREGATE GRADING

The plot is further divided into grading regions - fine, medium and coarse - suggested by the trends in fineness index. The orientations of the three bands of grading suggest strength to be proportional to unit weight within each band. The orientations of the lines separating the regions represent the author's opinion as to the underlying relationships suggested by the results. It is obvious from the results presented in Table 23 (from which Figure 29 was developed) that for the batches made with each grading the unit weight and strength increased with higher compactive effort over the entire range of gradings. Thus, contradictions within each grading region shown in Figure 29 are caused by batch to batch variation. If the batch to batch variation could be reduced sufficiently, the actual relationship would probably be observed as a series of fineness isobars for which strength would be proportional to density.

The slope of the line separating the two regions of compaction effort, while intended to suggest the inverse relationship between strength and unit weight, is perhaps exaggerated in the author's attempt to clarify his observations. However, as was shown in the section: Results of Unit Weight Tests on Cylinders Made by Rodding, the slope is not positive. This fact alone indicates strength to have been influenced as much by gradation as by density, and subjective examination of the plot suggests the influence was great enough to cause an inverse relationship of strength and density.

TABLE 23

AVERAGE RESULTS OF STRENGTH AND UNIT WEIGHT TESTS ON SPECIMENS COMPACTED BY RODDING AND TWENTY SECONDS OF VIBRATION

Grading No.	Fineness Index	Rodding		20-Sec. Vibration	
		Unit Weight pcf	Compressive Strength psi	Unit Weight pcf	Compressive Strength psi
1	3.61	148.72	3777	149.96	4325
2	3.09	147.89	4266	150.51	4635
3	4.15	148.47	3780	151.28	4209
4	3.47	149.62	3952	150.76	4422
5	3.72	148.60	3838	150.51	3909
6	3.98	149.23	3758	150.28	4086
7	3.56	149.23	4138	150.76	4298
8	3.69	149.89	4038	151.19	4380
9	3.70	149.23	3767	151.02	4245
10	3.14	148.28	4204	150.76	4525
11	2.45	148.21	4717	149.91	4917
12	2.65	148.21	4518	150.00	—
13	2.85	148.34	4732	150.76	4965
14	2.96	147.87	4265	150.59	4660
15	2.94	147.36	4241	150.68	4525
16	2.94	147.62	4386	150.93	4585
17	3.42	149.15	4141	150.08	4086
18	3.33	148.05	3930	150.17	4298
19	3.38	149.49	4174	150.76	4705
20	3.94	148.21	4633	150.76	4720
21	3.17	148.34	4244	150.76	4616
22	3.22	148.34	4280	150.76	4581
23	2.55	148.34	4518	150.00	4740
24	4.70	148.94	3661	151.19	4209
25	4.50	151.02	3696	151.27	—
26	4.30	148.00	3434	150.00	3626
27	4.30	149.87	3593	151.19	3979
28	4.30	148.64	3616	151.10	4218
29	4.25	148.81	3640	150.76	4253
30	3.88	149.55	3935	150.78	4262
31	3.86	148.21	4077	150.51	4457
32	3.91	148.72	3577	149.91	—
33	3.58	148.85	3829	150.76	3979

The results of the investigation indicate that the relationship of strength and unit weight was subordinate to the relationship of strength and grading, except in somewhat narrow bands or ranges of gradation fineness, and that for compacted concrete, strength must be considered part of a four dimensional relationship (strength, water-cement ratio, coarse aggregate grading, unit weight) even for a given maximum aggregate size.

Segregation during Vibration

The most extreme bleeding was observed in batches made with coarse gradings. Those specimens seen to bleed the worst during the twenty seconds of vibration were later sawed longitudinally and visually examined for settlement of the coarse particles. The segregation was only slight in even the worst condition and could not be considered detrimental.

Results of Remolding Tests

The average results are reported in Table 24 as the number of drops of the flow table and apparatus required to remold the specimen to a given depth. Homogeneity of variance was verified by the Foster-Burr test. ANOV 7, Table 25 showed remolding effort to be significantly ($\alpha = 0.05$) affected by coarse aggregate gradation. However, the remolding test did not provide as sensitive a measure of workability as the slump and compacting factor tests.

TABLE 24

AVERAGE RESULTS OF REMOLDING TESTS

Grading No.	Fineness Index	Remolding Effort (Number of Drops)
1	3.61	35.3
2	3.09	35.0
3	4.15	36.0
4	3.47	30.0
5	3.72	40.0
6	3.98	36.0
7	3.56	36.0
8	3.69	31.0
9	3.70	27.0
10	3.14	29.0
11	2.45	44.0
12	2.65	49.0
13	2.85	37.7
14	2.96	32.0
15	2.94	35.0
16	2.94	39.0
17	3.42	41.3
18	3.33	31.7
19	3.38	29.0
20	2.94	40.0
21	3.17	40.0
22	3.22	32.0
23	2.55	41.0
24	4.70	39.0
25	4.50	62.0
26	4.30	35.0
27	4.30	33.7
28	4.30	34.7
29	4.25	34.0
30	3.88	33.0
31	3.86	29.0
32	3.91	42.0
33	3.58	30.0

TABLE 25

ANOV 7 - REMOLDING EFFORT

Source of Variation	df	SS	MS	F	F(.05)
Gradation	32	2037.896	63.68	1.91*	1.73
Error	40	1334.762	33.37		

* Significant

At a level of significance of $\alpha = 0.025$, the effect of gradation could not be considered significant for the remolding test, whereas the slump and compacting factor tests would again indicate significance. Though the remolding test may well measure some aspect of workability other than those aspects measured by the slump and compacting factor, it cannot be considered as practical or as sensitive for evaluation purposes.

APPLICATION OF RESULTS

The slump and compacting factor test results agree with results of historical studies and again show workability to be influenced by coarse aggregate gradation. However, workability is of concern only as it affects the ease with which concrete can be placed or, in practice, only as it affects density for a given compaction effort. The unit weights obtained for specimens made with a reasonable compaction effort were not substantially affected by gradation. From a practical standpoint, then, it is concluded that typical variations in highway concrete gravel do not detrimentally affect the compactability of a low slump mix such as that used by the ISHC for slipform paving.

A comparison of the calculated percentages of variation in slump and strength attributable to gradation variability indicates that typical variations in natural gravel gradation are as important to strength as to slump. The influence of gradation on strength was seen to be direct and independent of other factors such as water-cement ratio, density and maximum aggregate size.

The results also provide information applicable both to traditional specifications and to the statistical specifications which are being advocated. In order to appreciate the

applicability of the results one must accept that gradation sometimes exceeds the ISHC No. 5 limits even though the sieve analysis reports do not reveal this. Field inspectors and others familiar with inspection procedures would be aware of this from knowledge of occurrences of "failures" which are not reported but rather qualified by additional tests. It was also shown in the section: Selection of Gradings Investigated that, with the standard deviations in percent passing obtained from statistical analysis of typical stockpiles, some gradings must be exceeding the specified limits. This should not be taken as criticism of inspection procedures, for in the opinion of the author the results indicate that gradation of natural gravel does not warrant tighter control than is now maintained. Strength was the only property seen to be severely affected by typical variations in gravel gradation, and reductions in strength appear to be outweighed by increases. It is evident, at least, that tighter control of gradation would not be justifiable without improving control of the other factors affecting variability of the concrete.

Along this same line of reasoning, considerations might well be given to a revised system of gradation control in which all sieve analysis results would be reported and gradation deemed acceptable as long as a certain percentage of individual tests and the average of several did not exceed the limits. This would allow identification of trends which

might not be observable under the present system as well as provide data from which the true variability in gradation could be ascertained.

There has been discussion about applying payment adjustments to a specification system such as described above [11], wherein the contractor would receive lowered unit payment for non-conformance. While the concept is sound, in the opinion of the author the results of this investigation raise sufficient question to require further investigation of the actual effect of variations before assuming the system is economically justified. A particular level of variation should not be considered detrimental until it is shown to increase the total project cost.

The investigation did not include evaluation of the effect of grading on properties such as permeability and shrinkage or aspects such as finishability. These characteristics are to a large extent dependent on water-cement ratio, the quantity and consistency of the paste and density of the compacted mixture. The water cement ratio was constant throughout the investigation. The yield, an indicator of cement content, was seen to vary no more than three percent as a result of the small variation in unit weight for concrete compacted with a reasonable effort. Though consideration might well be given to these other characteristics in future investigations, it appears they would not be critically affected by variations in coarse aggregate gradation of the magnitude occurring in typical concrete gravels.

SUMMARY AND CONCLUSIONS

The effect of various natural gravel gradings on selected properties of a portland cement concrete mixture was investigated by mixing and testing numerous batches in the laboratory. All mix variables other than grading were held constant in order to obtain information about the importance of the coarse aggregate gradation as a source of variation in properties of the mixture. A summary of the findings follows:

1. The coarse aggregate gradation affected slump significantly; the finer the grading, the lower the slump.
2. The coarse aggregate gradation affected the compressive strength significantly; the finer the grading, the higher the strength. The effect on strength was direct and independent of water cement ratio, unit weight and maximum aggregate size.
3. The coarse aggregate gradation significantly affected the compactability of the fresh concrete, but for a reasonable amount of compaction effort the effect was inconsequential. For a reasonable

compaction effort, the unit weight was not substantially affected by gradation.

The gradation of natural gravel used for concrete aggregate has been shown to fluctuate outside the present ISHC No. 5 limits as much as fifteen percent of the time. The various gradings which were examined in the investigation, taken as a set, represent the variations which were estimated to actually occur in concrete produced for highway pavement. In regard to the influence of these variations, the following conclusions are made on the basis of the results obtained in the investigation:

1. Variations in the gradation of natural gravel are as important to uniformity of strength as to uniformity of slump.
2. With a reasonable amount of vibration the effect of variations in the gradation of natural gravel on compactability can be overcome and uniform density attained.

RECOMMENDATIONS

The investigation was limited to natural gravel and to a particular low slump concrete mixture. Other investigations using different types of coarse aggregate are necessary for expanding inference to coarse aggregates in general. The effects observed in this investigation might not be significant in mixes with higher slump, and similar investigations should be conducted for other classes of mixtures which are of interest.

Based on the knowledge, results and experience obtained during the investigation, this section is a summary of procedures recommended for future investigations of a similar nature.

The grading envelope examined should be established from statistical data related to the type of aggregate, concrete and production conditions of interest to the investigator. The variation (standard deviation) of the percent passing any sieve size depends primarily on: (1) the type of aggregate (natural gravel, crushed stone, etc.), (2) the sieve sizes included in the gradation series and (3) the handling techniques from the plant to the time of batching in the concrete mixer. In general, the estimates of variation used for establishing the $\pm\ 3\hat{\sigma}$ boundaries of

the envelope should be realistically conservative. Overly conservative estimates would exaggerate the effect of grading variability, but underestimation would leave in doubt the significance of the effect. Verification of the norm grading, to which the $3\hat{\sigma}$ estimates will be applied, is a necessity. If the average grading is different from the norm implied by the grading limits, the envelope would be appropriately displaced toward the finer or coarser gradings. The details of the procedure described in the section: Selection of Gradings Investigated serve as the recommended approach for establishing the gradings to be investigated.

The replicate batches made with each grading and the various gradings should be randomized within the testing plan.

The number of gradings which should be examined is dictated as much by statistical ramifications as by the necessity to represent the types of variation which occur. The extreme, continuous fine and coarse gradings were shown to have the greatest effect on the properties measured in this investigation. These continuous gradings, extreme gap gradings such as Grading No. 33 and one or two gradings with fineness indices incremented between those of the extreme continuous gradings would assure data representative of the range in the values of the properties. However, this limited number of gradings would not facilitate establishment of the variance of the results within the gradings or

provide a reasonably adequate number of degrees of freedom for evaluating the variance resulting from the gradings ($\hat{\sigma}_g^2$). Ten gradings would provide a reasonable number for preliminary evaluation. If the variance of the results within the gradings was then shown to be homogeneous for each of the properties and the between batch mean squares shown to be comparable to those obtained in this investigation, one would be justified in not testing any more gradings. This procedure would affect the randomness of the experimental design if more gradings were required, and the researcher would be wise to consult the statistician associated with the project prior to finalizing his plan.

Also of importance to the analysis of variance is the number of batches made with each grading. Table 26 shows the expected number required to observe various differences in the means of the slump, strength and unit weight test results of any two gradings. The number of batches listed in the table is based on the between batch mean square of the respective ANOV's. Of the tests performed in this investigation the unit weight is seen to be the most critical in regard to number of tests. The researcher should determine the difference he considers important and establish the number of batches from Table 26 or from statistical references.

Replicate tests within a batch are not a statistical necessity. In comparison, replicate batches are of much

TABLE 26

NUMBER OF BATCHES REQUIRED TO OBSERVE DIFFERENCES BETWEEN GRADINGS (From Ostle [19])

Δ Slump (in.)	Δ Strength (psi)	Δ Unit Weight (pcf)	Number of batches needed for each grading*
0.25	300	1.3	22
0.50	600	2.4	7
0.75	900	3.4	4
1.00	1100	4.3	3

Δ = desired observable difference

* For: $\alpha = 0.05$, $\beta = 0.1$

greater importance than replicate tests within a batch. More than one test per batch is, of course, necessary for identifying the measurement variance; but, unless the researcher feels the need to evaluate the testing technique or to establish the significance of batch to batch variation, replicates within a batch need not be run.

The material control procedures and batching techniques described in the section: Procedures should be considered minimal. Despite the techniques used to maintain uniformity between batches, the batch to batch variance was shown to be significant in all ANOV's which allowed evaluation of that level. The author is not aware of any particular laboratory procedure which might have been utilized to reduce the batch to batch variation. Consultation with experienced laboratory personnel could possibly lead to improved control.

It is recommended that the following tests be performed in future investigations:

1. Slump
2. Compressive strength or modulus of rupture.
3. Unit weight after rodding in accordance with ASTM procedures.
4. Unit weight after compaction within the compacting factor apparatus.
5. Unit weight after compaction with an effort less than the 10 seconds of vibration used in this study but more than that provided by the compacting factor apparatus.

6. Air content.

7. Vebe test.

8. Segregation observations.

Although this appears to be a large number of tests, the effort required for several tests on each batch is small compared to that required to prepare the batch materials and to mix each batch. The slump, strength and unit weight of rodded specimens are essential for evaluation of the effect of grading variability on the properties commonly measured in the field. The compacting factor test provides a good measure of the effect of gradation on the density of unworked concrete and an indication of its effect on workability. Item 5 of the list would be an attempt to identify the compaction effort above which the effect of gradation on compactability is inconsequential. The results of this investigation indicate a level of compaction somewhat less than ten seconds of vibration is required. The Vebe test is recommended as another possible means of measuring workability and could be run in conjunction with the slump test without any complication of the laboratory routine. Specimens should be made and examined for gradings seen to bleed during vibration. Air content tests should be run to confirm mixture responses to grading changes.

For convenience of computer processing of data and use of common statistical analysis techniques it would be advisable to obtain an equal number of test values within each grading and for each batch.

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APPENDIX

APPENDIX

TABLE 27

RESULTS OF SLUMP TEST FOR EACH BATCH

Grading No.	Slump* (in.)	Grading No.	Slump* (in.)
1	1.25	17	1.25
1	1.50	17	1.25
1	1.25	17	1.00
1	1.00	18	1.50
1	1.50	18	1.75
1	1.25	18	1.50
1	1.25	19	1.00
2	1.00	20	1.25
2	1.00	20	0.25
3	1.75	21	1.00
3	2.00	22	1.00
4	1.25	23	0.25
5	1.75	24	2.00
6	1.75	24	1.75
7	0.50	24	1.50
8	1.50	25	1.50
8	2.00	26	2.25
8	1.25	26	2.25
9	1.75	26	2.50
10	1.50	27	2.00
10	1.00	27	1.75
11	0.50	27	2.00
11	1.25	28	2.00
11	0.50	28	1.50
12	0.50	28	1.50
13	1.00	29	1.75
13	1.00	29	1.75
13	1.00	29	1.25
14	1.00	30	1.00
14	1.50	30	1.75
14	1.25	31	1.25
15	1.00	31	1.50
15	1.00	32	1.75
15	1.00	32	2.00
16	0.50	32	1.50
16	1.25	33	1.50
16	0.50		

* ASTM C143

TABLE 28

RESULTS OF UNIT WEIGHT TESTS FOR EACH BATCH

Grading No.	Compacting Factor (pcf)	10 Seconds of Vibration (pcf)	20 Seconds of Vibration (pcf)	Rodded (pcf)	
				Test 1	Test 2
1	135.46	145.15	149.49	148.21	148.98
1	137.76	144.90	150.51	148.21	147.96
1	135.20	145.41	149.24	146.94	147.96
1	136.22	145.92	150.00	148.98	148.72
1	137.25	147.96	150.77	149.74	149.49
1	136.99	147.45	149.24	149.49	149.49
1	136.99	145.41	150.51	149.49	148.47
2	134.95	146.68	149.49	147.70	147.96
2	135.71	146.43	151.53	147.96	147.96
3	139.29	146.94	150.77	147.96	148.98
3	136.74	145.41	151.79	148.72	148.21
4	138.01	145.92	150.77	149.75	149.49
5	136.48	146.43	150.51	148.98	148.21
6	138.01	147.45	151.28	150.00	148.47
7	128.83	146.43	150.77	149.75	148.72
8	139.54	146.17	151.28	148.98	149.24
8	136.22	146.68	151.28	149.75	149.49
8	136.22	146.43	151.02	147.96	147.96
9	135.71	146.94	151.02	149.49	148.98
10	136.48	145.41	150.77	147.45	148.72
10	133.93	146.43	150.77	148.47	148.47
11	129.85	144.39	149.49	147.96	147.96
11	129.59	145.41	150.00	147.70	147.71
11	131.63	145.15	150.26	149.24	148.72
12	130.36	146.68	150.00	148.21	148.21
13	133.67	146.17	149.75	147.19	147.55
13	132.91	146.43	150.77	147.45	147.19
13	131.38	147.96	151.79	151.02	149.75
14	134.44	145.15	149.24	146.94	146.43
14	134.69	144.90	151.53	148.73	148.21
14	132.91	146.17	151.02	148.47	148.47
15	132.65	146.43	150.00	145.15	145.92
15	135.20	145.66	151.02	147.45	147.96
15	133.16	145.92	151.02	148.72	148.98
16	133.93	145.41	150.77	147.45	147.96
16	135.46	144.64	151.02	147.19	147.19
16	129.59	146.68	151.02	147.45	148.47

TABLE 28

CONTINUED

Grading No.	Compacting Factor (pcf)	10 Seconds of Vibration (pcf)	20 Seconds of Vibration (pcf)	Rodded (pcf)	
				Test 1	Test 2
17	132.65	145.92	150.51	150.00	149.75
17	134.69	146.17	149.24	148.47	148.47
17	134.69	145.41	150.51	149.49	148.72
18	136.48	145.15	149.49	148.47	147.70
18	138.01	144.39	150.51	148.21	147.71
18	131.63	145.92	150.51	147.96	148.21
19	134.69	146.94	150.77	148.98	150.00
20	133.67	146.94	150.77	148.47	147.96
20	130.36	146.43	150.77	148.21	148.21
21	128.57	145.92	150.77	148.21	148.47
22	131.89	146.17	150.77	148.47	148.21
23	128.57	146.68	150.00	148.47	148.21
24	136.48	146.94	151.79	148.98	149.24
24	141.33	148.21	150.77	150.26	150.51
24	135.97	147.96	151.02	147.70	146.94
25	135.71	148.47	151.28	150.51	151.53
26	136.48	146.68	148.21	149.24	149.24
26	140.31	146.17	150.77	147.70	147.96
26	140.56	146.17	151.02	147.45	146.43
27	136.22	146.94	151.53	149.49	151.02
27	140.31	147.45	150.77	150.51	148.47
27	140.82	146.68	151.28	150.51	149.24
28	136.74	146.17	149.49	147.70	148.47
28	137.76	147.45	152.55	148.47	149.24
28	137.76	145.92	151.28	148.98	148.98
29	136.74	145.15	150.00	148.47	149.49
29	138.27	147.19	150.25	148.47	147.96
29	134.18	146.68	152.04	149.24	149.24
30	137.50	146.94	152.55	150.51	150.25
30	139.54	145.41	151.02	148.21	149.24
31	138.27	144.90	149.75	147.70	147.19
31	136.48	147.96	151.28	149.49	148.47
32	134.44	145.92	151.02	149.49	150.00
32	138.27	150.51	148.98	148.98	148.21
32	138.01	145.66	149.75	147.96	147.70
33	133.42	147.19	150.77	150.00	147.70

TABLE 29

RESULTS OF 7-DAY COMPRESSIVE STRENGTH TESTS

FOR EACH BATCH*

Grading No.	Rodded Cylinders* (psi) 1	Rodded Cylinders* (psi) 2	Vibrated Cylinders (psi)	Grading No.	Rodded Cylinders* (psi) 1	Rodded Cylinders* (psi) 2	Vibrated Cylinders (psi)
1	—	—	—	17	4279	4103	—
1	—	—	—	17	4421	4315	—
1	3608	—	4139	17	3784	3943	4086
1	3767	3679	4280	18	—	—	—
1	3944	3891	4528	18	3731	3643	4245
1	—	—	—	18	4138	4209	4351
1	—	—	—	19	4191	4156	4705
2	4226	4173	4475	20	4492	4757	4599
2	4368	4297	4793	20	4633	4633	4846
3	3696	3855	—	21	4297	4191	4616
3	3696	3873	4209	22	4262	4297	4581
4	3890	4014	4422	23	4527	4509	4740
5	3820	3855	3909	24	—	—	—
6	3625	3890	4086	24	3608	3625	—
7	4050	4226	4298	24	3643	3767	4209
8	3820	4085	4227	25	3837	3554	—
8	4244	4032	4528	26	3289	3289	—
8	4103	3943	4351	26	3448	3519	3626
9	3837	3696	4245	26	3448	3608	—
10	4138	3961	4280	27	3679	—	—
10	4421	4297	4775	27	3448	3501	—
11	—	—	—	27	3554	3767	3979
11	4951	4704	—	28	—	—	—
11	4739	4474	4917	28	3661	3572	4227
12	4509	4527	—	28	3678	3554	4209
13	4369	—	—	29	3519	—	—
13	4333	4315	4528	29	3661	3643	4050
13	5376	5270	5412	29	3890	3837	4457
14	4138	4067	—	30	4067	4156	4262
14	4120	4439	4669	30	3767	3749	—
14	4562	4262	4652	31	—	—	—
15	4262	3625	4669	31	4156	3997	4457
15	4279	4297	4457	32	—	—	—
15	4598	4386	4457	32	3466	3484	—
16	4439	4509	4439	32	3625	3731	—
16	3961	4173	4492	33	3891	3767	3979
16	4562	4669	4846				

* ASTM C192 and C39

TABLE 30

RESULTS OF REMOLDING TEST FOR EACH BATCH

Grading No.	Remolding Effort*	Grading No.	Remolding Effort*
1	26	17	47
1	31	17	41
1	32	17	36
1	50	18	36
1	35	18	29
1	35	18	30
1	38	19	29
2	37	20	40
2	33	20	40
3	34	21	40
3	38	22	32
4	30	23	41
5	40	24	34
6	36	24	49
7	36	24	34
8	28	25	62
8	31	26	41
8	34	26	33
9	27	26	31
10	23	27	38
10	35	27	32
11	43	27	31
11	52	28	40
11	37	28	29
12	49	28	35
13	40	29	36
13	35	29	30
13	38	29	36
14	31	30	39
14	28	30	27
14	37	31	28
15	34	31	30
15	38	32	47
15	33	32	38
16	34	32	41
16	33	33	30
16	50		

* Number of drops of flow table

TABLE 31

ANOV TABLE FOR SIMPLE LINEAR REGRESSION

OF SLUMP ON FINENESS INDEX

	df	SS	MS	F	F(.05)
Regression	1	9.5056	9.5056	92.2*	13.4
Residual	71	7.32312	0.10314		

* Significant

TABLE 32

ANOV TABLE FOR SIMPLE LINEAR REGRESSION

OF STRENGTH ON FINENESS INDEX

	df	SS	MS	F	F(.05)
Regression	1	13118506.78	13118506.78	240.69*	12.8
Residual	120	6540360.13	54503.01		

* Significant